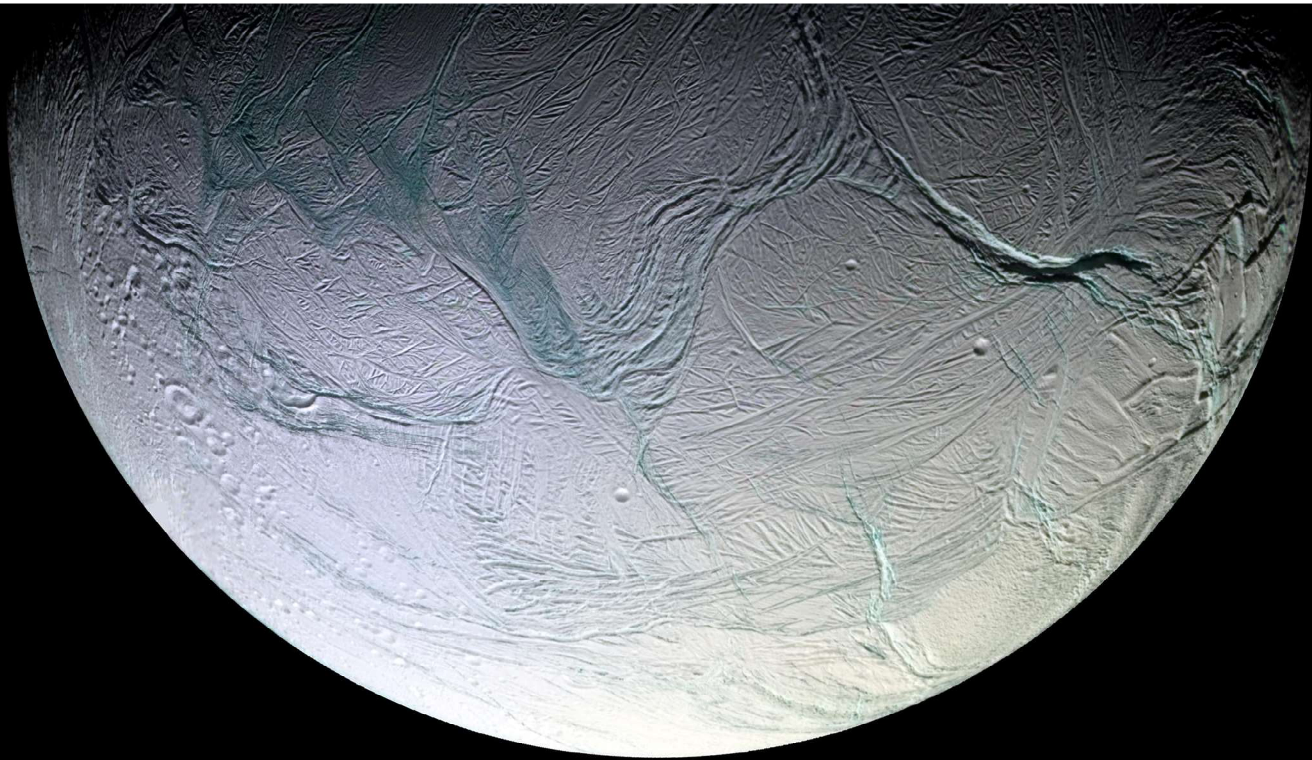


Plume Induced Contamination and Erosion

A colloquium presentation to DLR Göttingen, Germany

September 12, 2018

Carlos Soares

Technical Group Supervisor – Contamination Control Engineering

Propulsion, Thermal and Materials Engineering Section

Jet Propulsion Laboratory

California Institute of Technology

Executive Summary

- Mission science objectives supporting detection of organics and life are extremely challenging
- Science instrumentation is evolving with increasing sensitivity to spacecraft induced environments
- Characterization and mitigation of plume induced contamination and erosion effects is critical to space exploration and achievement of mission science objectives
- Existing measurements/data, both from ground-based chamber tests and on-obit flight experiments, is very limited
- Engineering plume induced contamination and erosion models exhibit significant levels of uncertainty due to limitations in available measurements/data
- Knowledge gaps are known and can be addressed through ground-based chamber testing and on-orbit flight experiments
- There is a need to establish and implement a road map for the future

Agenda

- Introduction to JPL and the Propulsion, Thermal and Materials Engineering Section
- Contamination Control Engineering at JPL
- Introduction to thruster induced contamination and erosion
  - Gas-phase contamination
  - Liquid-phase contamination and erosion
  - Solid-phase contamination erosion
  - Electric propulsion induced contamination
- ISS plume induced contamination and erosion model development and application
  - Supporting chamber data used in the ISS model development
  - Supporting flight experiment data - NASA SPIFEX and PIC plume induced contamination experiments and on-orbit measurements
  - Erosion testing and modeling
  - Application of the engineering models to ISS, Shuttle and ISS visiting vehicles
- PIC-II flight experiment (a follow-on to PIC)
- Plume induced contamination and erosion for deep-space and planetary missions
  - Potential impacts to the detection of organics and life detection
  - Mars 2020 plume contamination (rover mission)
  - Europa Clipper plume contamination and erosion (orbiter mission)
  - Europa Lander (lander mission)
- Needed improvements in the characterization of plume induced contamination and erosion
  - Knowledge gaps
  - Ground-based chamber testing
  - On-orbit flight experiments
- The need for a roadmap for the future
- Conclusion

Jet Propulsion Laboratory
California Institute of Technology

The Jet Propulsion Laboratory (JPL) is the leading U.S. center for robotic exploration of the solar system, and has 19 spacecraft and 10 major instruments carrying out planetary, Earth science and space-based astronomy missions

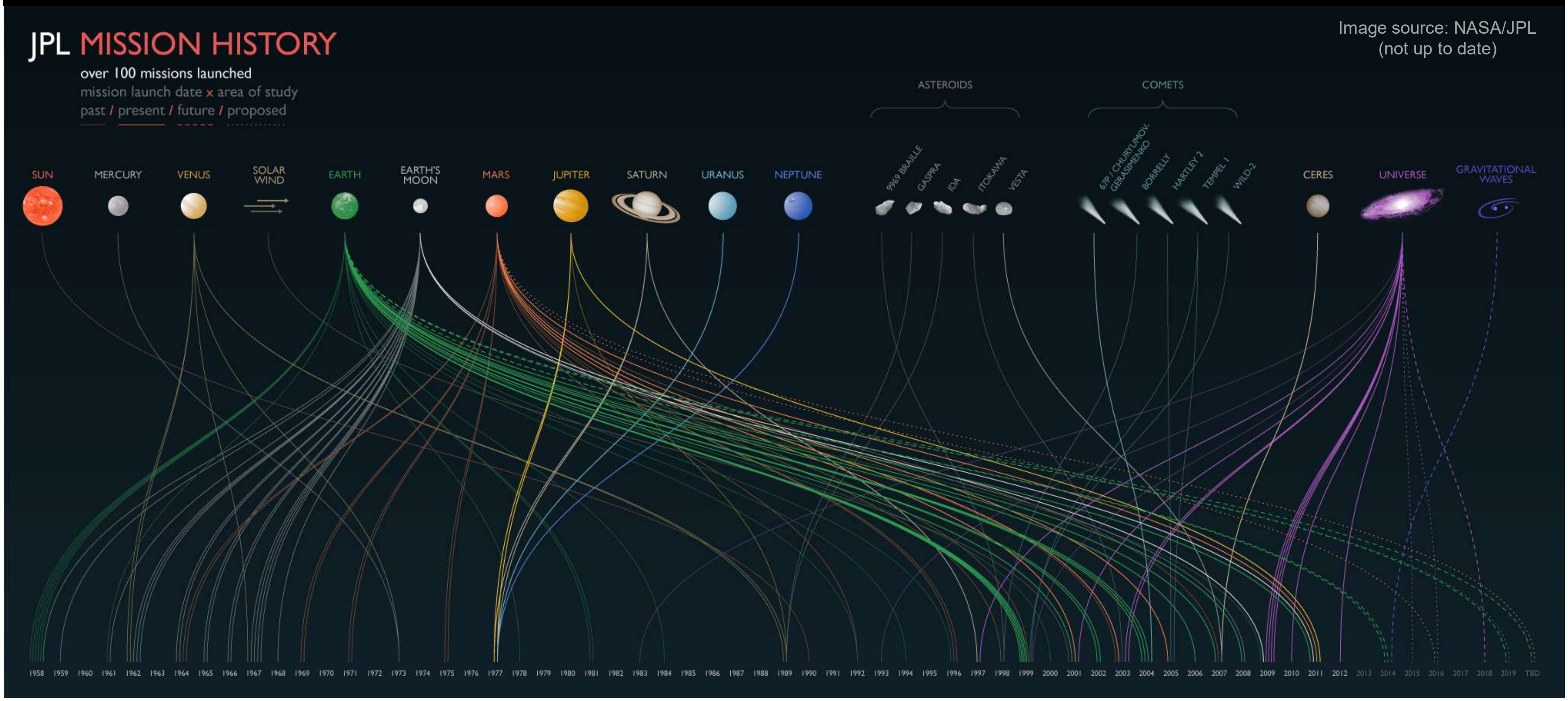
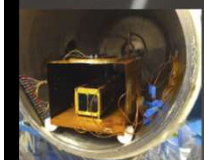


Image source: NASA/JPL
(not up to date)

Section 353 - Propulsion, Thermal and Materials Engineering Section

Contamination Control

We provide contamination control engineering expertise for technology development and flight projects from concept through mission end-of-life.



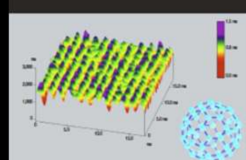
Thermal vacuum test of LMRST-Sat

InSight lander propulsion leak and proof testing

Artist's concept of InSight lander on Mars

Analytical Chemistry

We provide excellence in chemistry-based science and engineering. We are expert users of state of the art analytical chemistry equipment critical for materials development and characterization as well as surface/contamination evaluation. We develop new geochemical instruments as well as develop/use Aerogel materials for both technology and flight applications.



C-60 MOLECULES: Published in SCIENCE Vol 253, 91 c60b

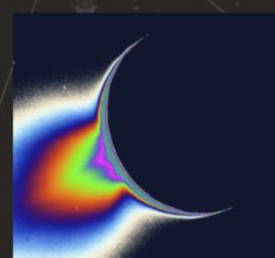
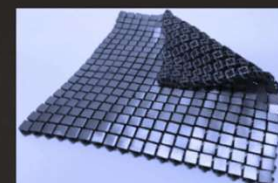


Image of Enceladus showing the fountain-like spray from the south polar region

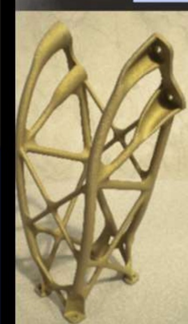
Illustration of one of the twin Mars Exploration Rovers

Materials

We provide materials engineering leadership for the design of JPL flight systems, as well as testing and evaluation of materials and assemblies for risk reduction. We also provide key support in the infusion of new materials and processes into flight projects.



Additively manufactured 3-D metallic fabric



Example of 3-D printed aircraft part

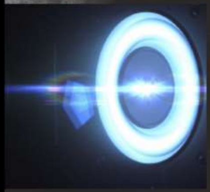
JPL-developed RoboSimian limbed robot

Gradient alloy optics mount

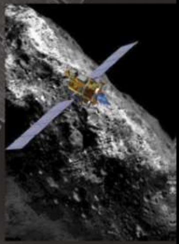
Section 353 - Propulsion, Thermal and Materials Engineering Section

Electric Propulsion

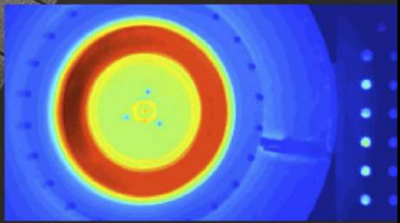
We support NASA mission needs in the area of Electric Propulsion over the full mission life cycle from technology development through flight implementation and operations. We also provide physics-based modeling and analysis expertise for technology applications and flight systems.



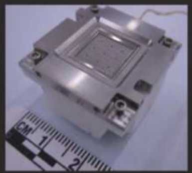
Solar electric propulsion thruster



Deep Space 1 near asteroid, artist's concept



Plume analysis for HERMeS thruster

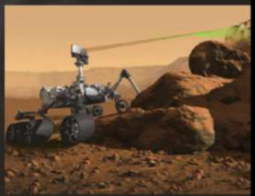


Microfluidic electrospray propulsion thruster

Chemical Propulsion

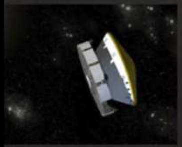
We provide Chemical Propulsion leadership, design, analysis and testing for technology and flight programs throughout the entire design cycle from concept to mission operations. We also provide advanced flow control design concepts and implementation approaches for instruments and flight experiments.

Low-Density Supersonic Decelerator (LDSD) flight test



Mars 2020 artist's concept

LDSD in test chamber

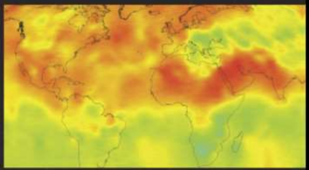


Spacecraft in its cruise phase between launch and final approach to Mars, artist's concept

Thermal Systems

We lead and support thermal systems engineering development of science instruments and spacecraft during the entire JPL project life cycle. We apply state of the art technologies and proven techniques to control temperatures of flight hardware in order to meet customer needs and achieve mission goals within available resources.

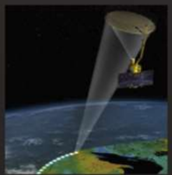
Orbiting Carbon Observatory-2 launch preparation



Orbiting Carbon Observatory-2 carbon dioxide map

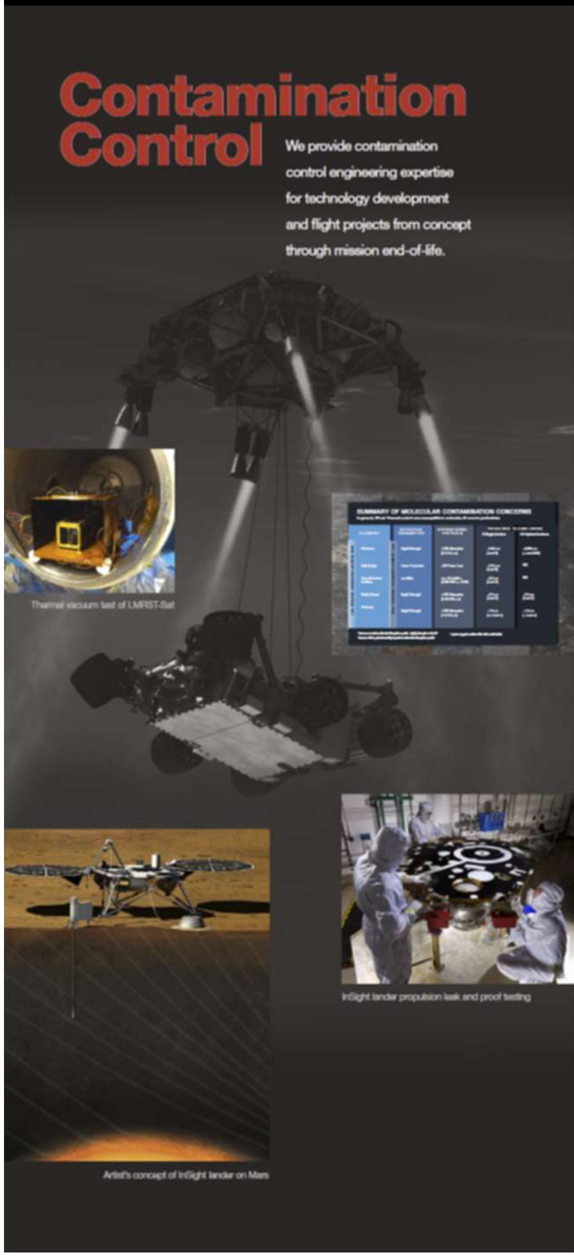
Mars Science Laboratory in test chamber

Gale Crater from Mars orbit



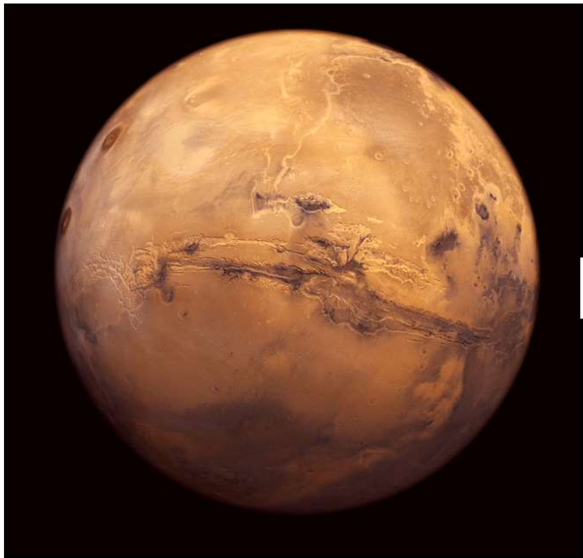
Artist's rendering of the Soil Moisture Active Passive (SMAP) satellite.

Contamination Control Engineering



353D
Contamination Control Engineering

Carlos E. Soares, Group Supervisor

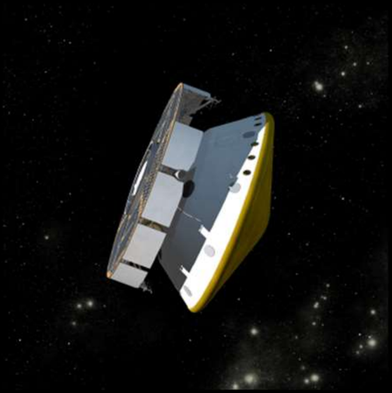


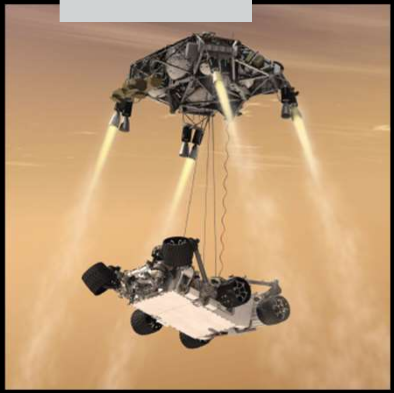
MARS MISSIONS

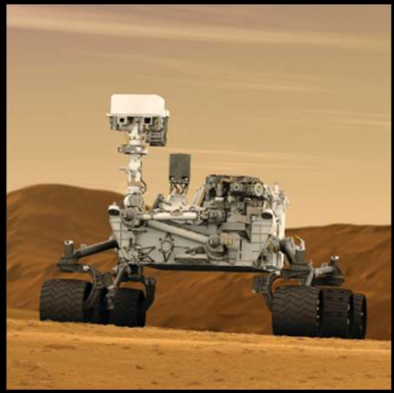
InSight [2018]

InSight

Mars 2020

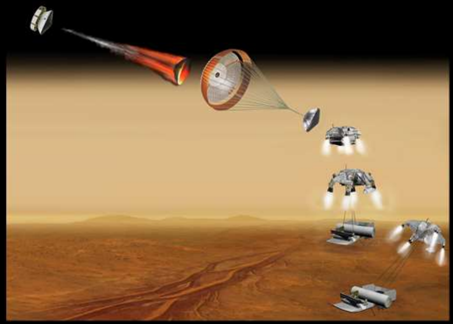






CONCEPTS

Mars Sample Return



NeMO - Next Mars Orbiter

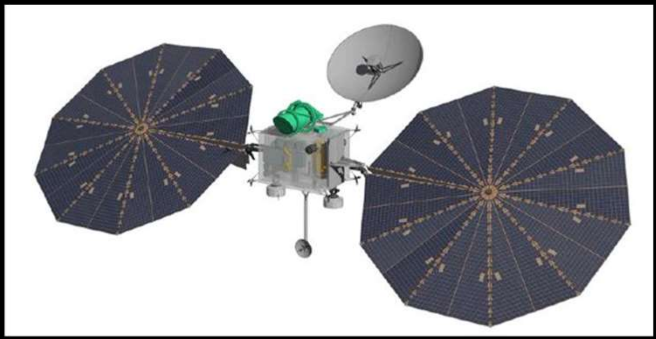
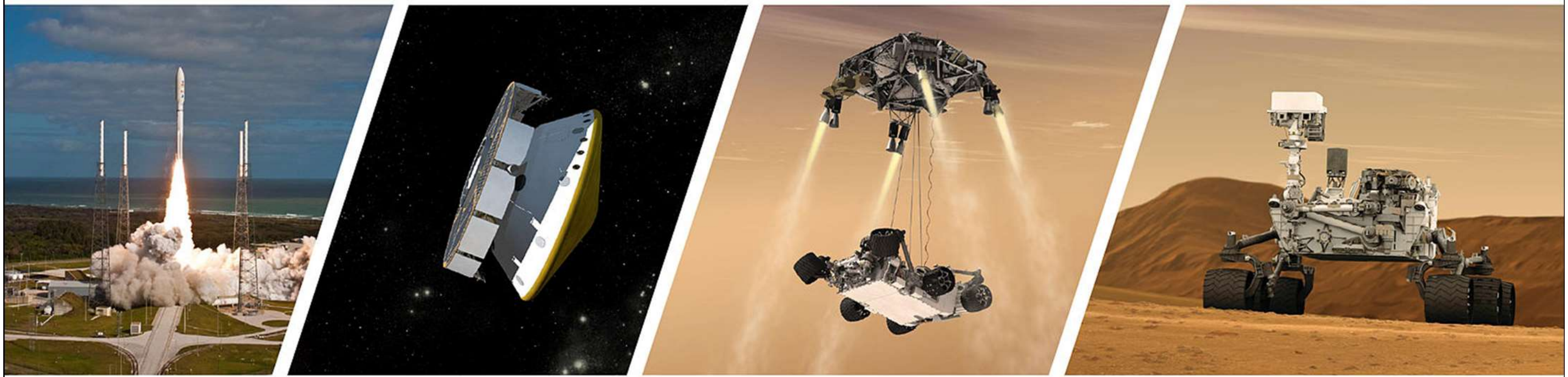


Image source: NASA/JPL

Mars 2020 Mission Timeline



LAUNCH
- Atlas V
- Period: Jul/Aug 2020

CRUISE/APPROACH
- 8 to 9-month cruise
- Arrive Jan/Mar 2021
- No changes from MSL (equivalent checkout capability, etc.)

ENTRY, DESCENT & LANDING
- MSL EDL system: guided entry and powered descent/Sky Crane
- 25 x 20 km landing ellipse*
- Access to landing sites ±30° latitude, ≤ 0 km elevation*
- ~950 kg rover
- Technology enhancements under consideration

SURFACE MISSION
- Prime mission is one Mars year (669 days)
- Latitude-independent and long-lived power source
- Ability to drive out of landing ellipse
- Direct (uplink/downlink) and relayed (downlink) communication
- Fast CPU and large data storage

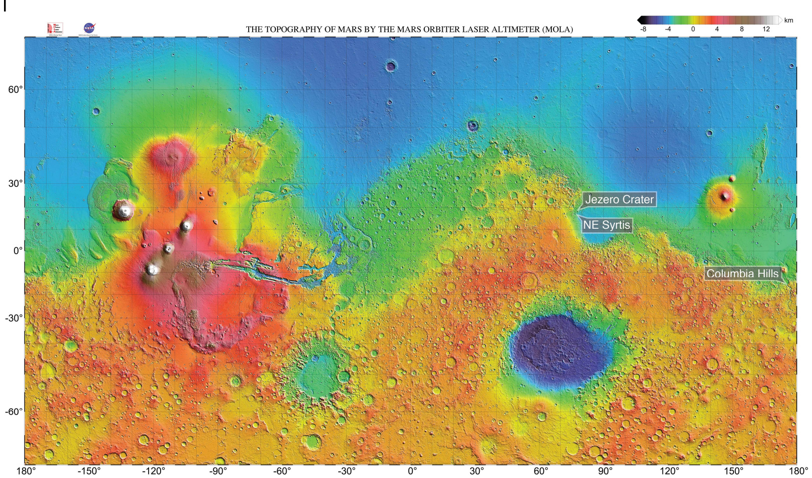
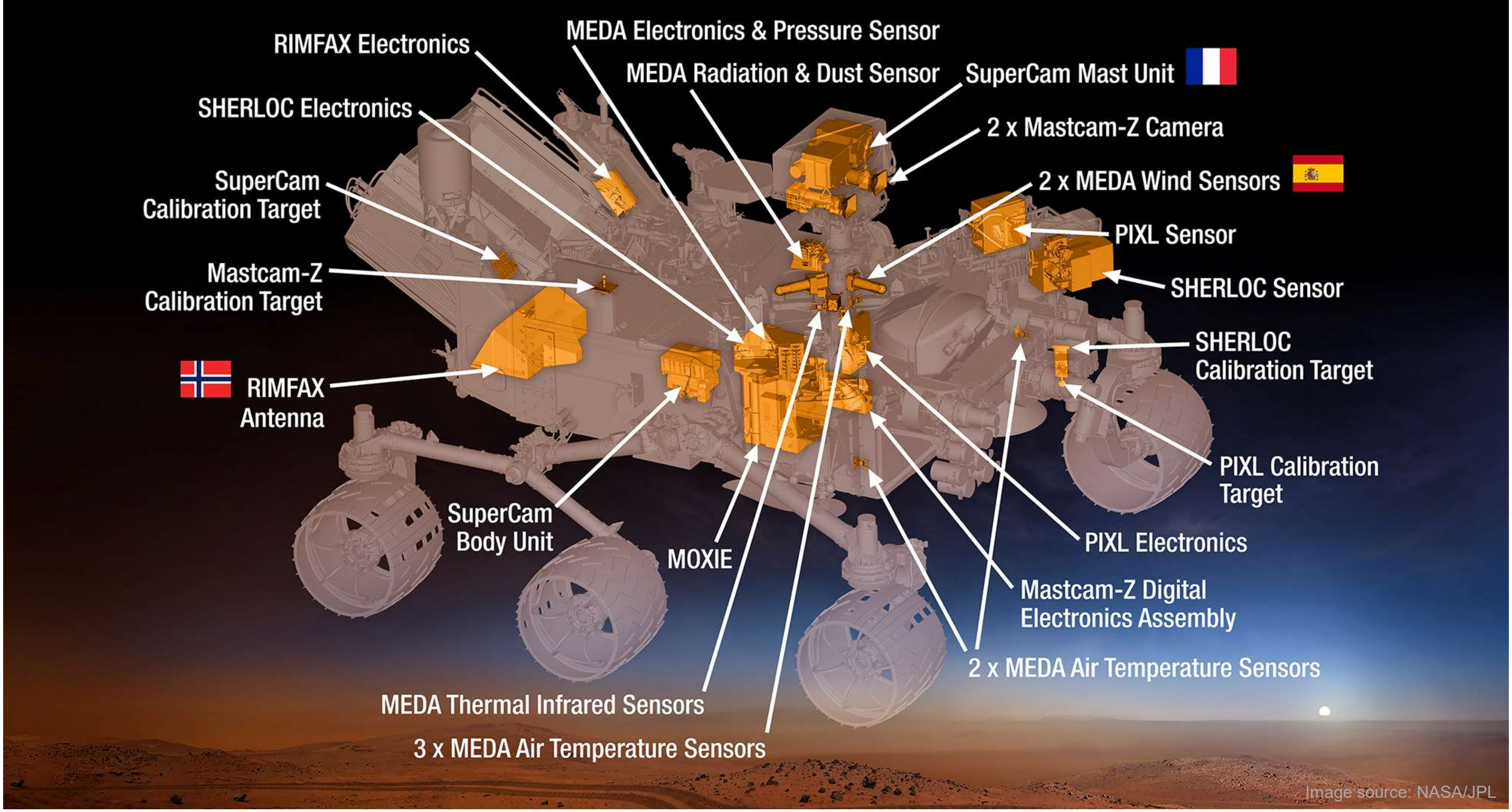


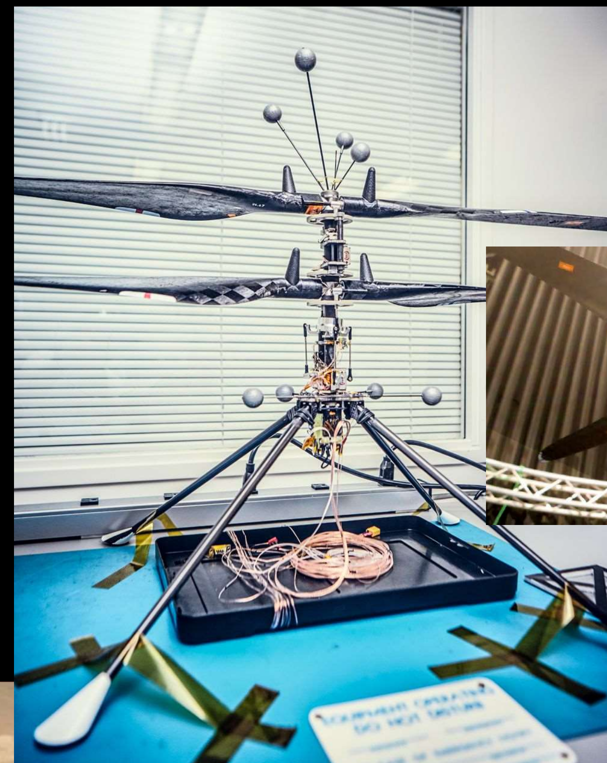
Image source: NASA/JPL

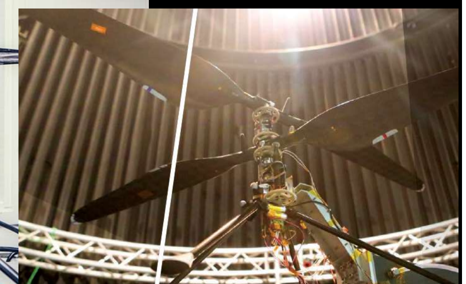
Mars 2020 Instruments / Science

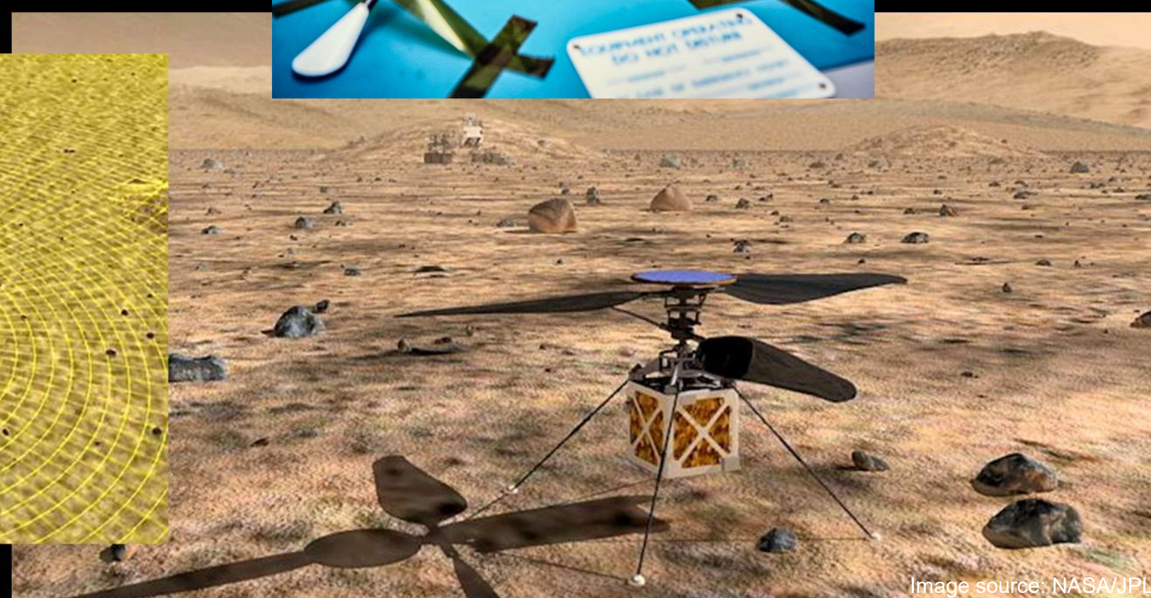


Mars Helicopter

- The Mars helicopter is a lightweight robotic helicopter and a pair of counter-rotating blades
- The blade span is designed for operation in the Martian atmosphere (7 Torr CO_2 atmosphere)
- The Mars helicopter will be solar powered, with enough power for repeated takeoffs and landing, with an endurance of 2 to 3 minutes of flight per Martian day for a distance of 500 m
- Tethered flight tests are being conducted under a 7 Torr CO_2 atmosphere at the large 25-ft Space Simulator at JPL (Environmental Test Facility)



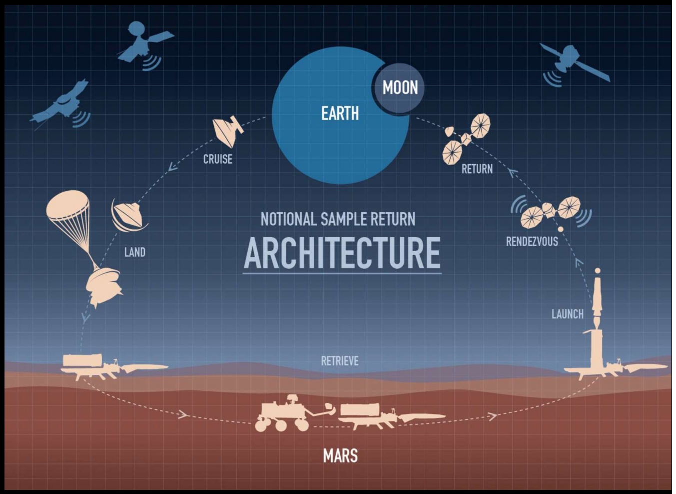




Potential Mars Sample Return (MSR)

Current advanced technology development for a robotic Mars Sample Return (MSR) architecture involve a campaign of three missions:

- MSR-C (fulfilled by Mars 2020) will collect and cache samples with a rover
- MSR-L would retrieve the Cache Canister and launch it into Mars orbit using a lander, rover and a Mars Ascent Vehicle (MAV)
- MSR-O would locate and capture the Orbital Sample (OS) in Mars orbit and return it to Earth



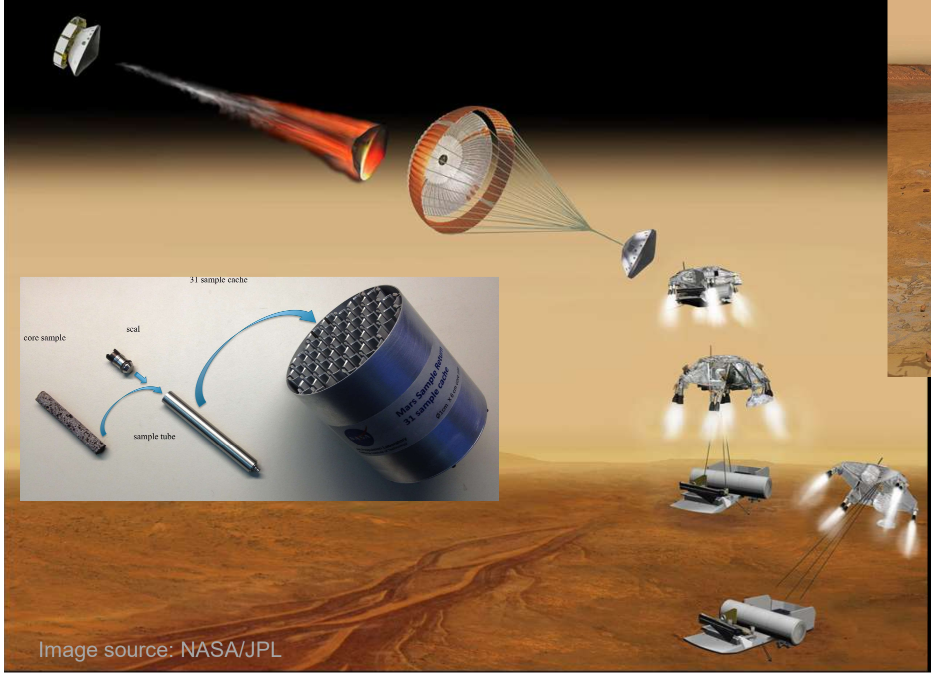
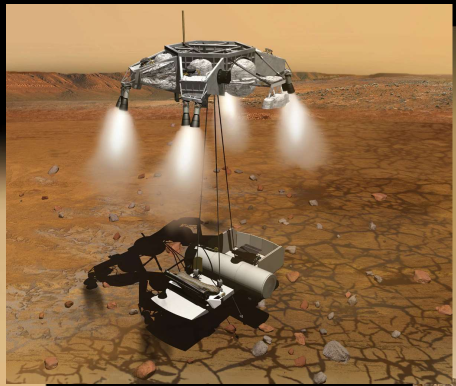
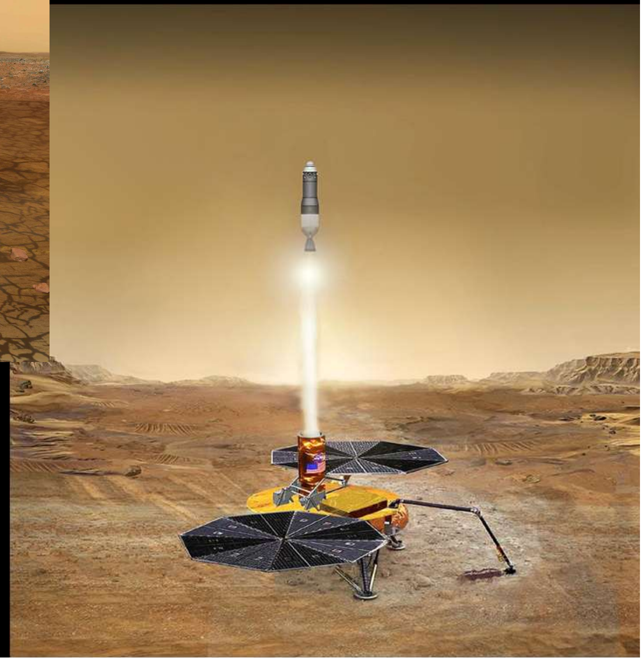
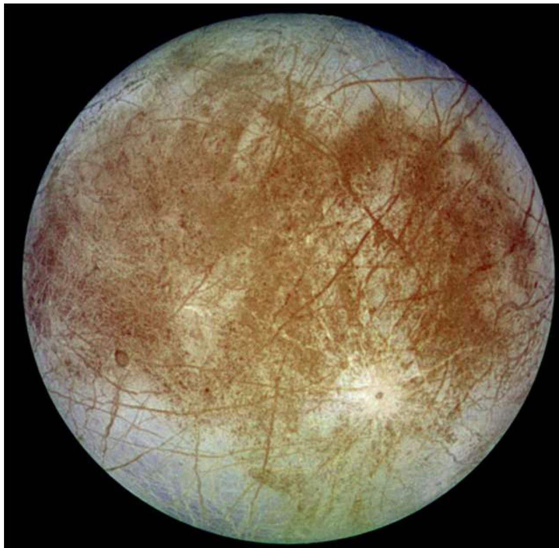


Image source: NASA/JPL



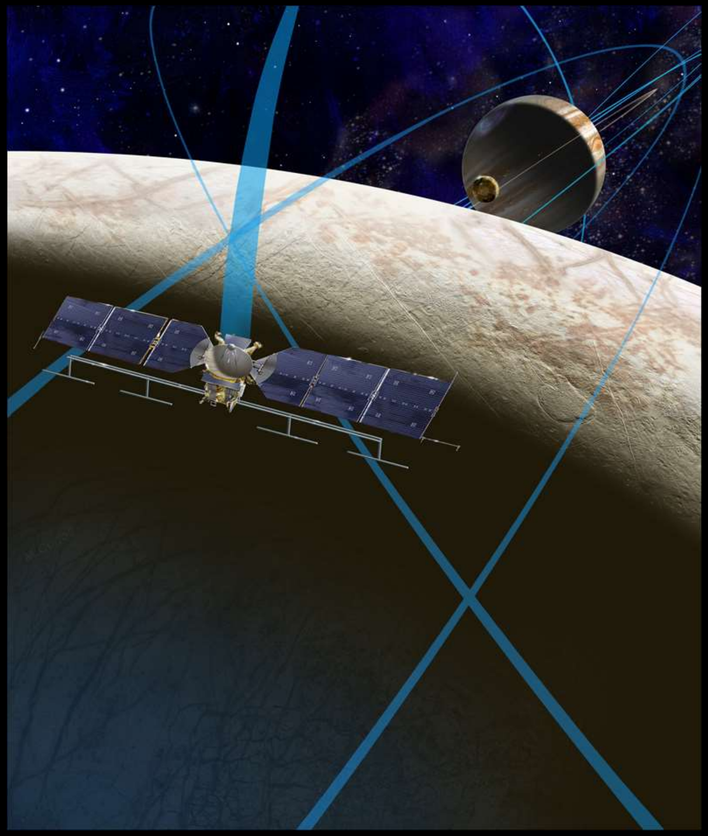


Pre-Decisional Information
For Planning and
Discussion Purposes Only



ICY MOONS

OUTER SOLAR SYSTEM



Europa

Enceladus

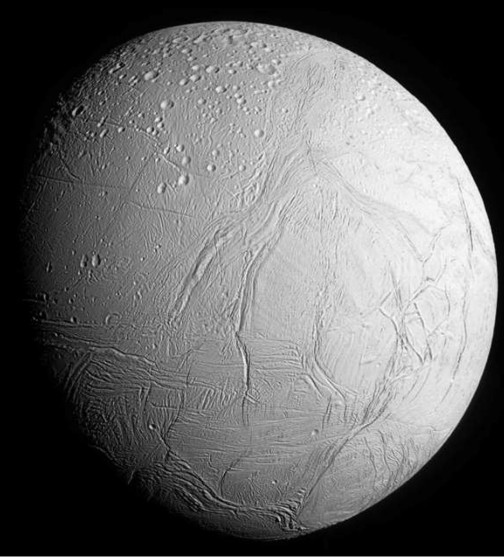


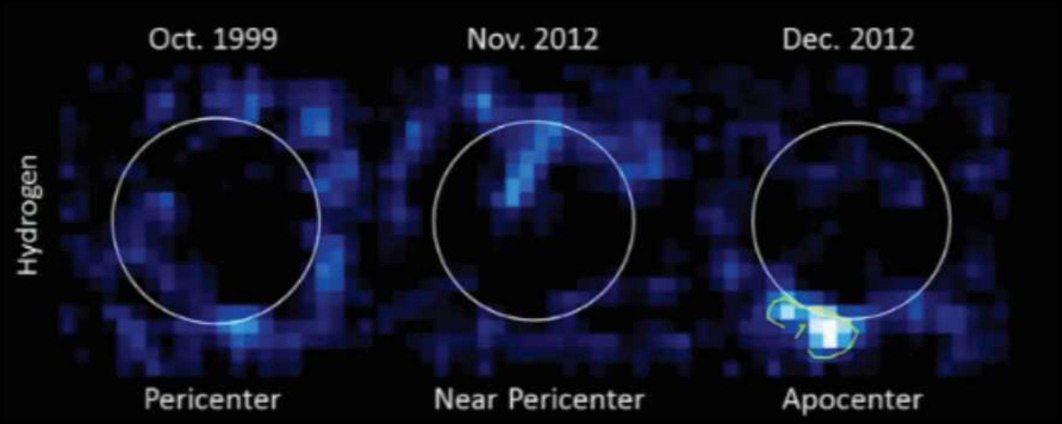
Image source: NASA/JPL

Europa

Europa Clipper (Orbiter)

Mission in Phase B – Preliminary Design

- *Orbiter will have a high-sensitivity mass spectrometer to measure composition of Europa plumes.*
- *Modeling interactions of Europa exosphere and plumes with orbiter thruster plumes (and materials outgassing).*



Hubble Ultraviolet images showing signs of plumes near Europa's south pole. [visible-light image of Europa has been added as a visual aid]

Image source: NASA/JPL

Europa Lander Concept

Mission in Phase A

Mission Concept Review (MCR): March 2017

- *Modeling thruster plume induced contamination of the science site on the surface of Europa*

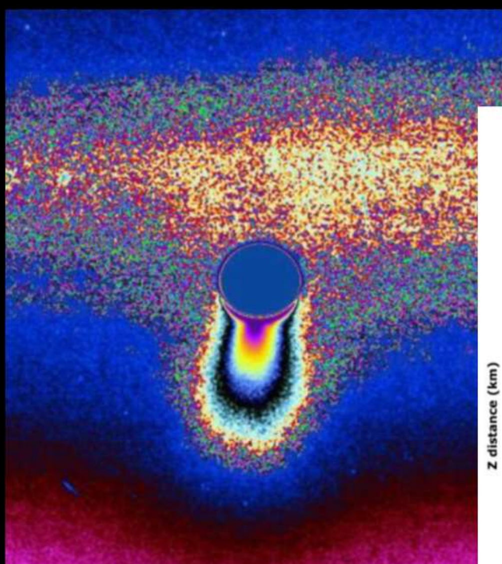
Pre-Decisional Information
For Planning and Discussion Purposes Only

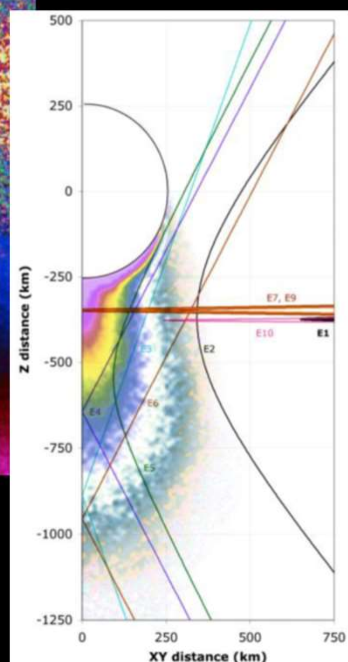
Enceladus

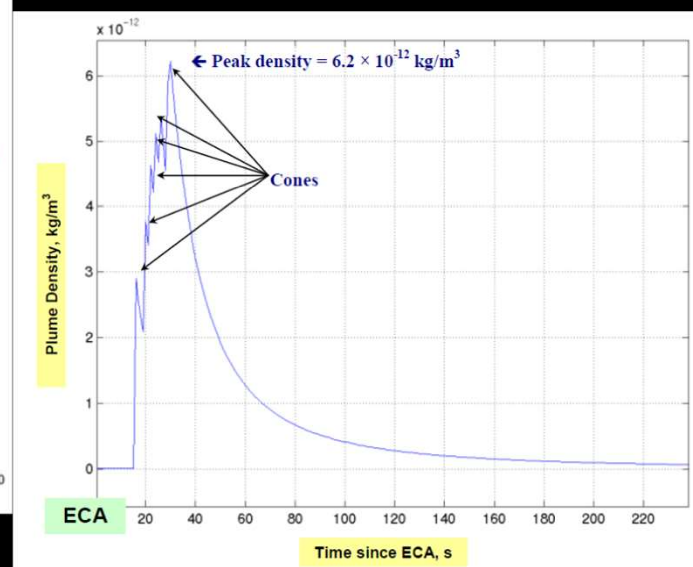
Plume and Jet modeling

Cassini data has been used to develop an engineering model of the Enceladus plume density, as a function of flyby altitude. These methodologies are being applied to modeling low altitude Enceladus flybys in future missions.

Image source: NASA/JPL

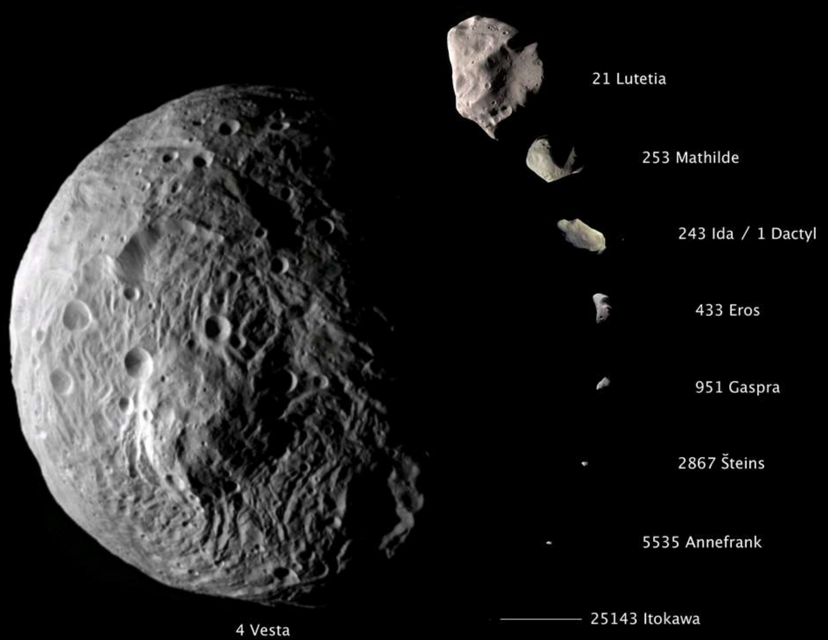






Reference: Sarani, S., *"Enceladus Plume Density Modeling and Reconstructions for Cassini Attitude Control System,"* AIAA 2010-2035, April 2010.

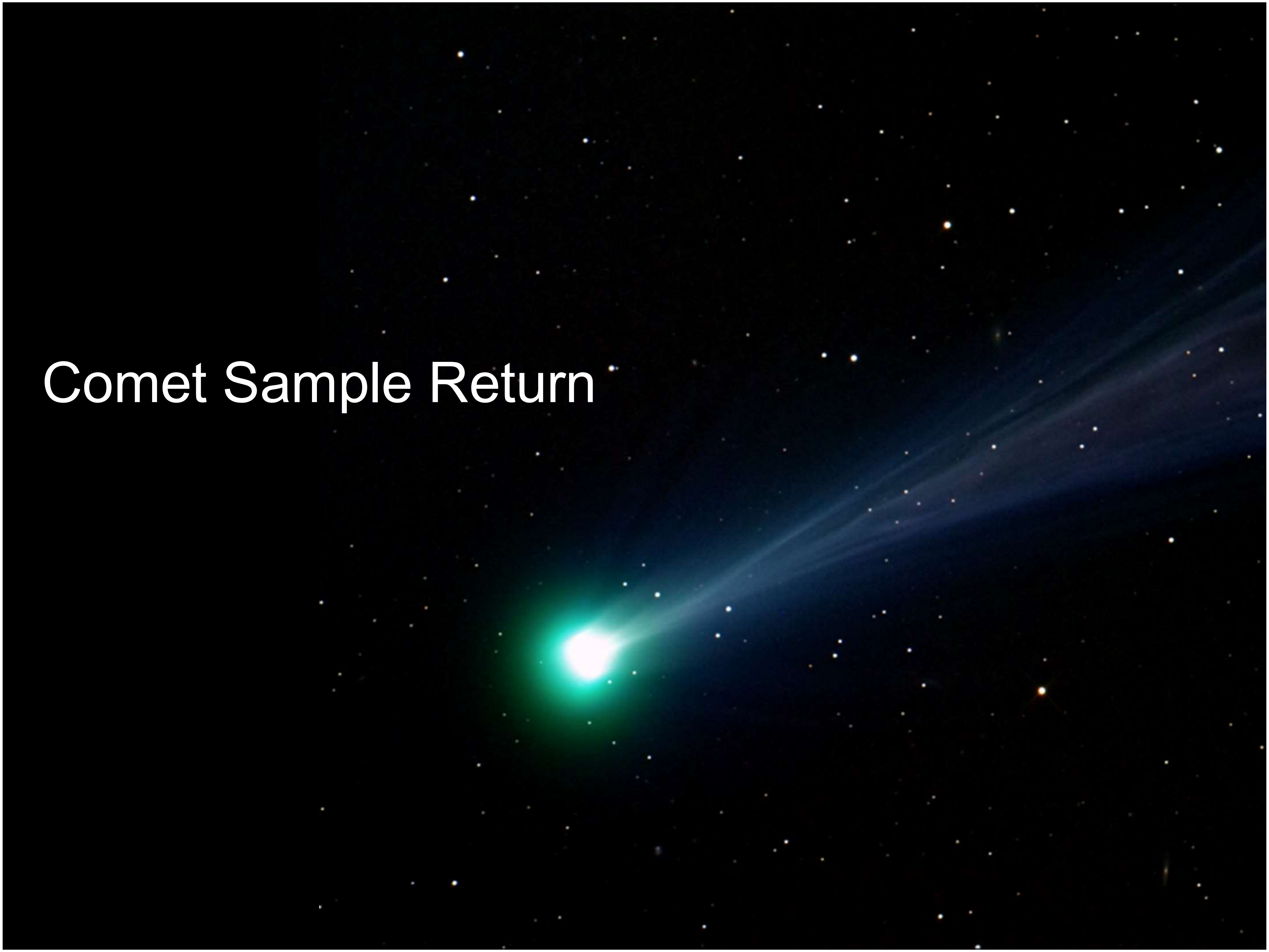
ASTEROIDS



Psyche

Image source: NASA/JPL

Comet Sample Return



Comet Sample Return Technology

Comet Sample Return

BiBlade is used in a Touch-and-Go (TAG) mission architecture where the spacecraft maneuvers to the surface of a comet, and deploys a sampling tool at the end of a robotic arm to the comet surface

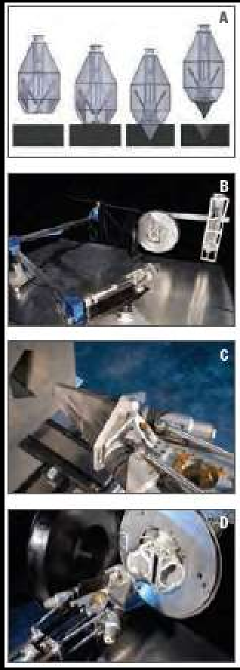
The robotic arm transfers the sampler to a sample chamber in the Sample Return Capsule (SRC)

A lid stored on the sampler is released over an SRC sample chamber to encapsulate the sample for return to Earth

Comet and interstellar dust analyzer (analyzes chemical composition of particles in the comet's coma)

Dust flux monitor (measures size and frequency of dust particles in the coma)

- **Thruster plume induced contamination**
- Contamination control of sampling tool, measurement station and instrumentation, Sample Return Capsule
- Materials outgassing induced contamination



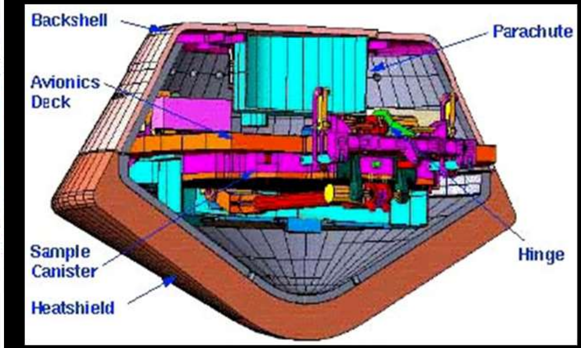
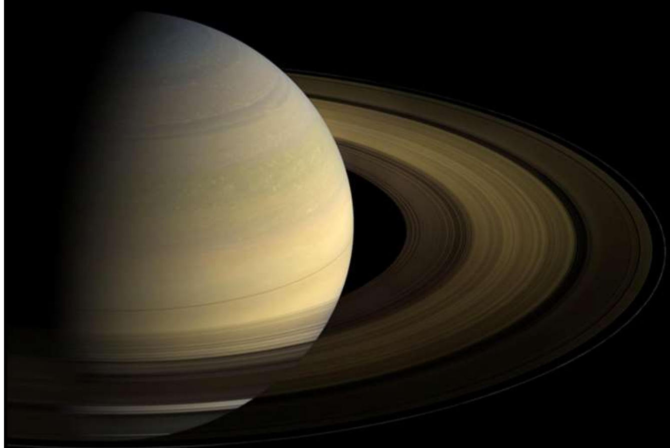
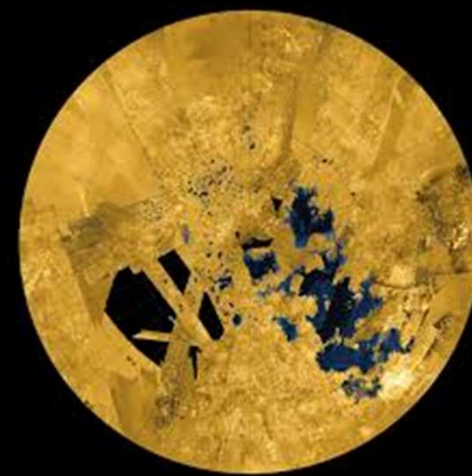


Image source: NASA/JPL

Other Potential Missions



Titan
[Orbiter & Probe]



Venus

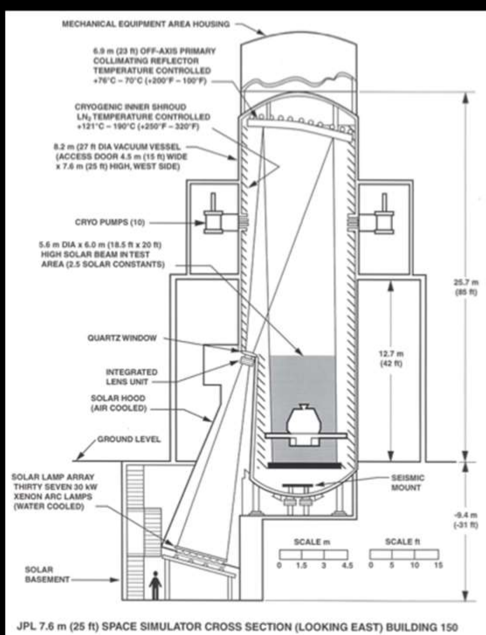
Image source: NASA/JPL

Environmental Test Laboratory (ETL) Space/Solar Simulator Facilities

The Environmental Test Laboratory (ETL) provides all JPL projects with facilities for thermal, thermal-vacuum, solar-thermal-vacuum, vibration, mechanical shock and acoustic testing for all types of space flight hardware.

Contamination Control:

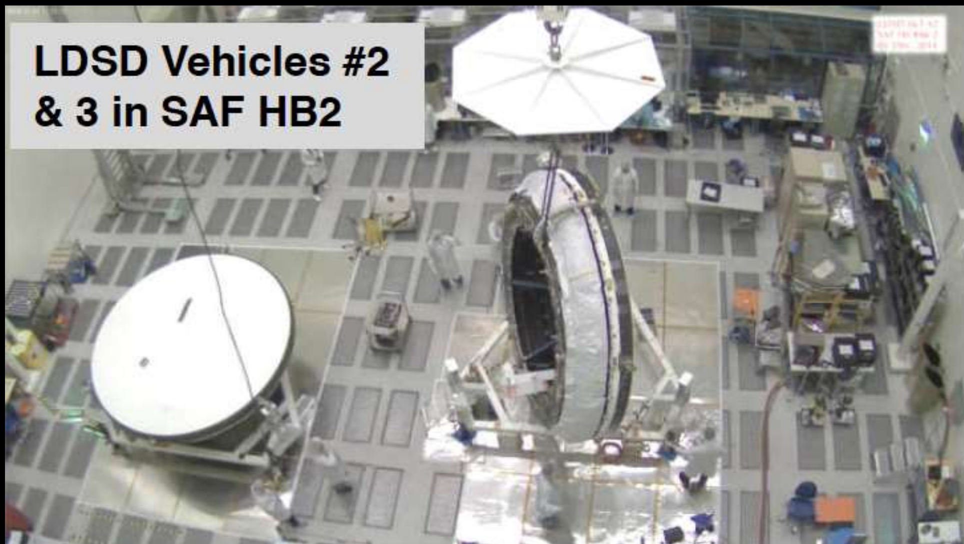
- **Thermal vacuum baking and testing (qualification, proto-flight, flight acceptance, planetary protection)**
- **CQCM/TQCM monitoring and verification of exit criteria**
- **NVR and particle testing/monitoring**



JPL 7.6 m (25 ft) SPACE SIMULATOR CROSS SECTION (LOOKING EAST) BUILDING 150

Image source: NASA/JPL

Mission Integration & Testing
Spacecraft Assembly Facility



The Spacecraft Assembly Facility (SAF) houses high bays one and two:

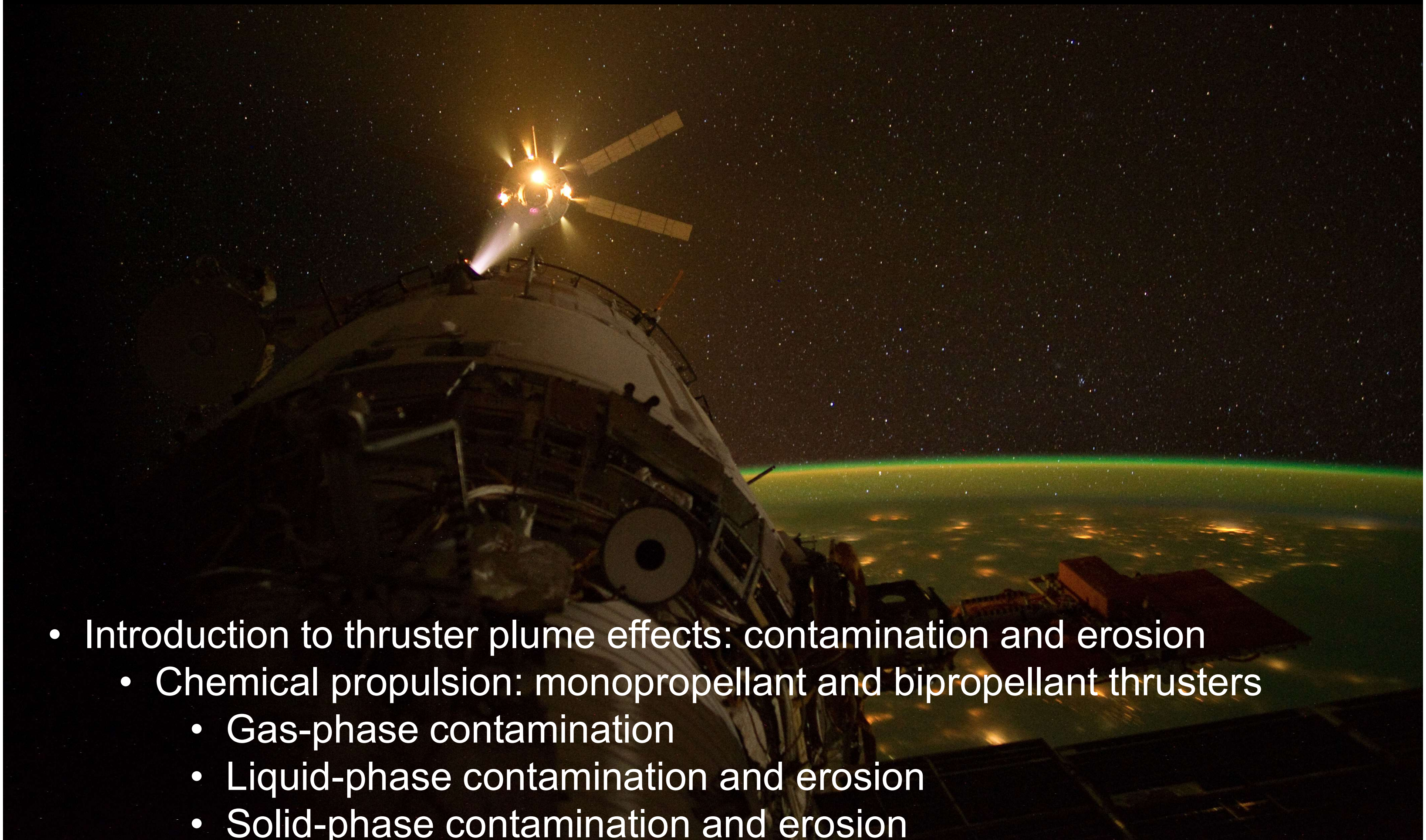
- High bay one (HB1) is nearly 14 meters tall
- High bay two (HB2) has a width, length and height of approximately 21 meters

Contamination Control:

- **Cleanroom environmental monitoring/control**
- **NVR and particle testing/monitoring**

Image source: NASA/JPL

Plume Effects: Contamination and Erosion



- Introduction to thruster plume effects: contamination and erosion
  - Chemical propulsion: monopropellant and bipropellant thrusters
    - Gas-phase contamination
    - Liquid-phase contamination and erosion
    - Solid-phase contamination and erosion
  - Electric propulsion induced contamination

Image source: NASA/JSC

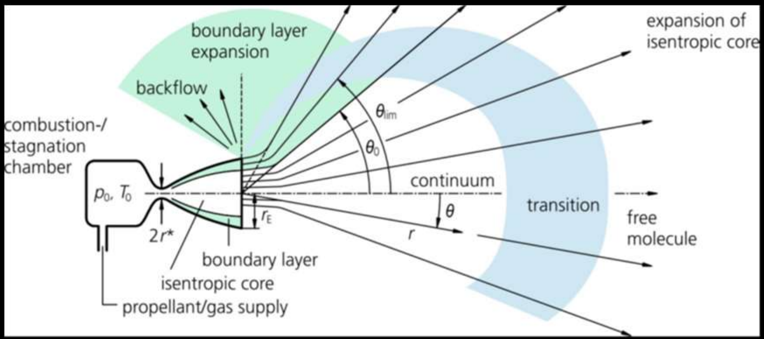
Chemical Propulsion: Monopropellant and Bipropellant Thrusters

Monopropellant (Hydrazine)

- Plume constituents:
  - Gas-phase: H_2, N_2, NH_3, H_2O, CH_4, CO_2, CO, HCL, Hydrazine, C_6H_7N (aniline)
  - Liquid-phase: Hydrazine, C_6H_7N (aniline)
  - Solid-phase (particulates): alumina/iridium (catalyst fine ejecta), Fe, non-volatile residue
- Lower performance (Isp)
- Lower plume velocities

Bipropellant (MMH/NTO)

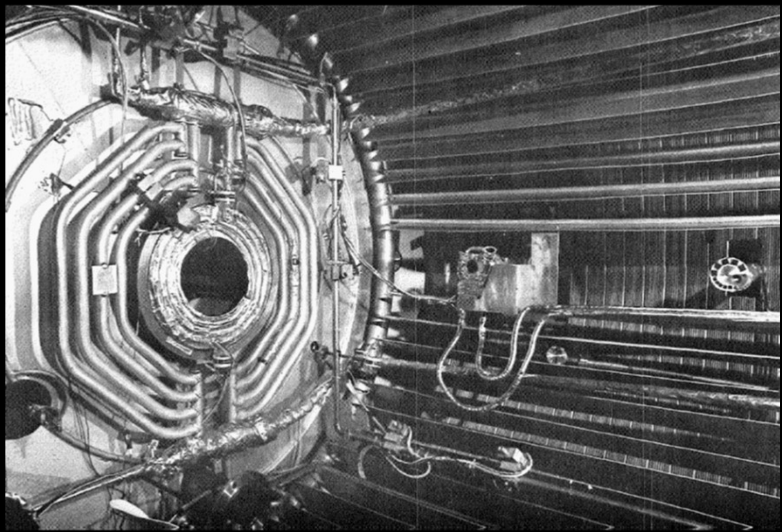
- Plume constituents:
  - Gas-phase: H_2, N_2, H_2O, CH_4, CO, CO_2, H, NO, O, OH, O_2
  - Liquid-phase: MMH-nitrate
  - Solid-phase (particulates): iron nitride, Fe, non-volatile residue
- Higher performance (Isp)
- Higher plume velocities

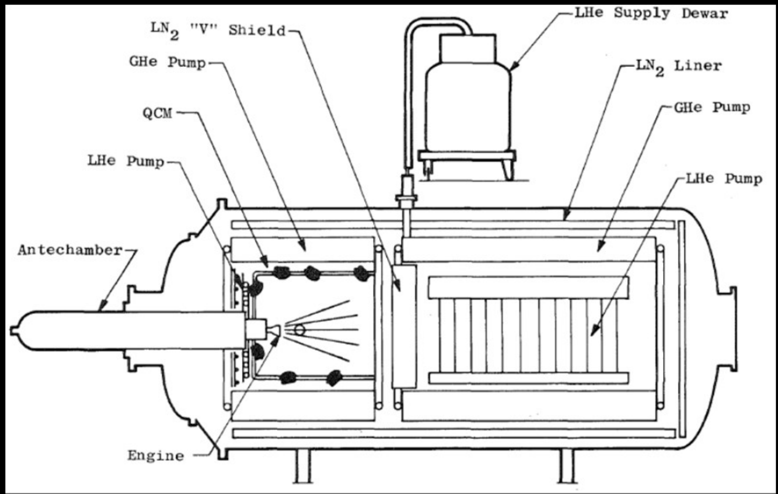


Source: Alt, R.E., "Bipropellant Engine Plume Contamination Program, » AEDC-TR-29-28, December 1979.

Gas Phase Contamination

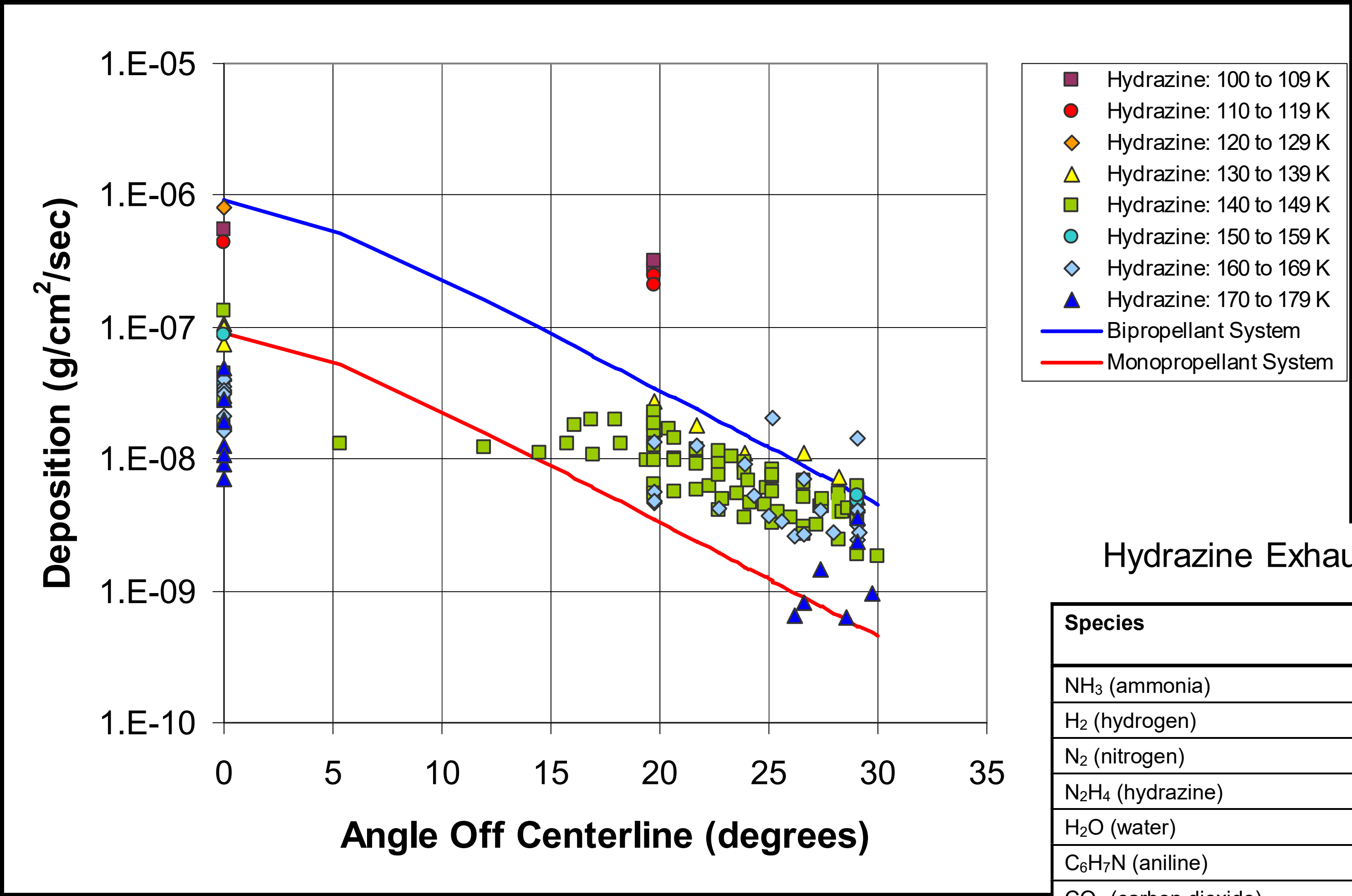
- Gas-phase constituents can condense at cryogenic temperatures in the form of a molecular deposit
    - Contamination impacts to missions to outer solar system (icy moons) due to low operating temperatures of spacecraft surfaces
- Steady-state is well characterized though CFD/DSMC modeling; however, transients still lack characterization
- The U.S. Air Force Arnold Engineering Development Center (AEDC) conducted chamber measurements of gas-phase condensation on low temperature surfaces in the 70's and 80's





Source: Alt, R.E., "Bipropellant Engine Plume Contamination Program," AEDC-TR-29-28, December 1979.

Monopropellant Thruster Induced Contamination



Hydrazine Exhaust Composition

Species	Condensation Temperature (K)
NH_3 (ammonia)	106
H_2 (hydrogen)	5
N_2 (nitrogen)	25
N_2H_4 (hydrazine)	162
H_2O (water)	166
C_6H_7N (aniline)	178
CO_2 (carbon dioxide)	83
Fe (iron)	1362
NVR (non-volatile residue)	

Source: Williams, W.D. and Powell, H.M., "Experimental Study of the Plume Characteristics of an Aged Monopropellant Hydrazine Engine," AEDC-TR-29-2, April 1979.

Liquid Phase Contamination

- Liquid-phase constituents can produce both contamination (transient and permanent) and erosion (mechanical damage)
    - Discrete non-uniform deposits and erosion
    - Contamination impacts to all missions with plume impingement on sensitive surfaces
- Engineering models have been developed (e.g., Trinks, Soares)
- Chamber measurements conducted by ESA/DLR (Trinks, Dettleff, Grabe), U.S. Air Force, NASA, Keldysh/RSC-Energia (Russia)
- On-orbit flight measurements conducted by NASA (PIC, SPIFEX)

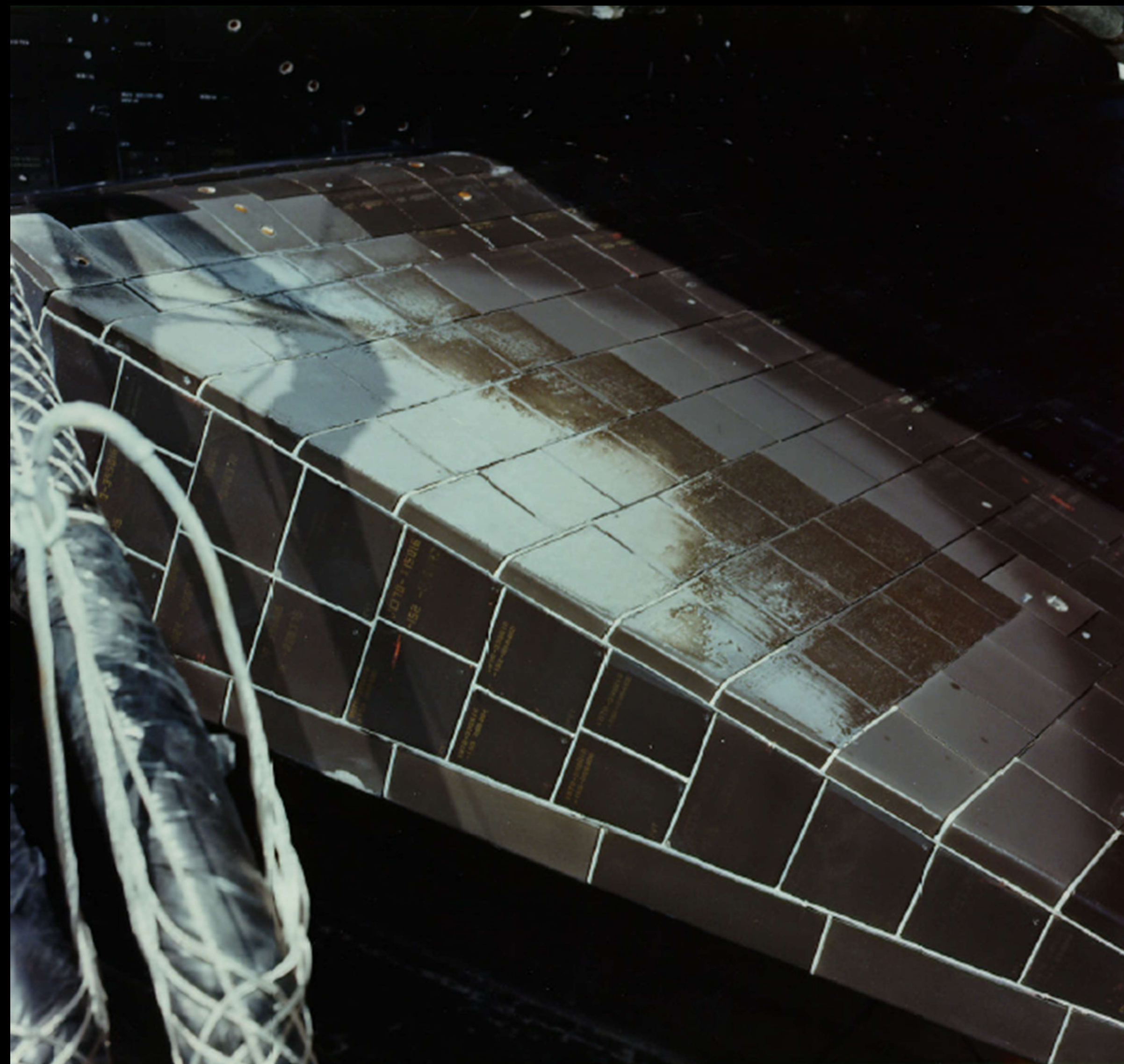
Source: Trinks, H., "Experimental investigation of the exhaust plume flow fields of various small bipropellant and monopropellant thrusters," AIAA Paper 87- 1607 (1987).

Dettleff, G., Grabe, M., "Basics of Plume Impingement Analysis for Small Chemical and Cold Gas Thrusters", RTO-RTO-EN-AVT-194, NATO Science & Technology Organization (2011).

Orlandi, M, et al; “Need for a tool for the preliminary analysis of bipropellant plume impingement effects on contamination sensitive surfaces,” SPIE Opitcs + Photonics, Systems Contamination: Prediction, Control, and Performance 2016, Proceedings of SPIE, Vol. 9952, 995209, 2016.

Liquid Phase Erosion

Observed post-flight damage on the Space Shuttle Orbiter Body Flap



Source: Koontz, S.L., Melendez, O., Zolensky, M, and Soares, C.; “SPIFEX Contamination Studies,” NASA JSC 27399, May 1996.
NASA JSC Photo S83-29867

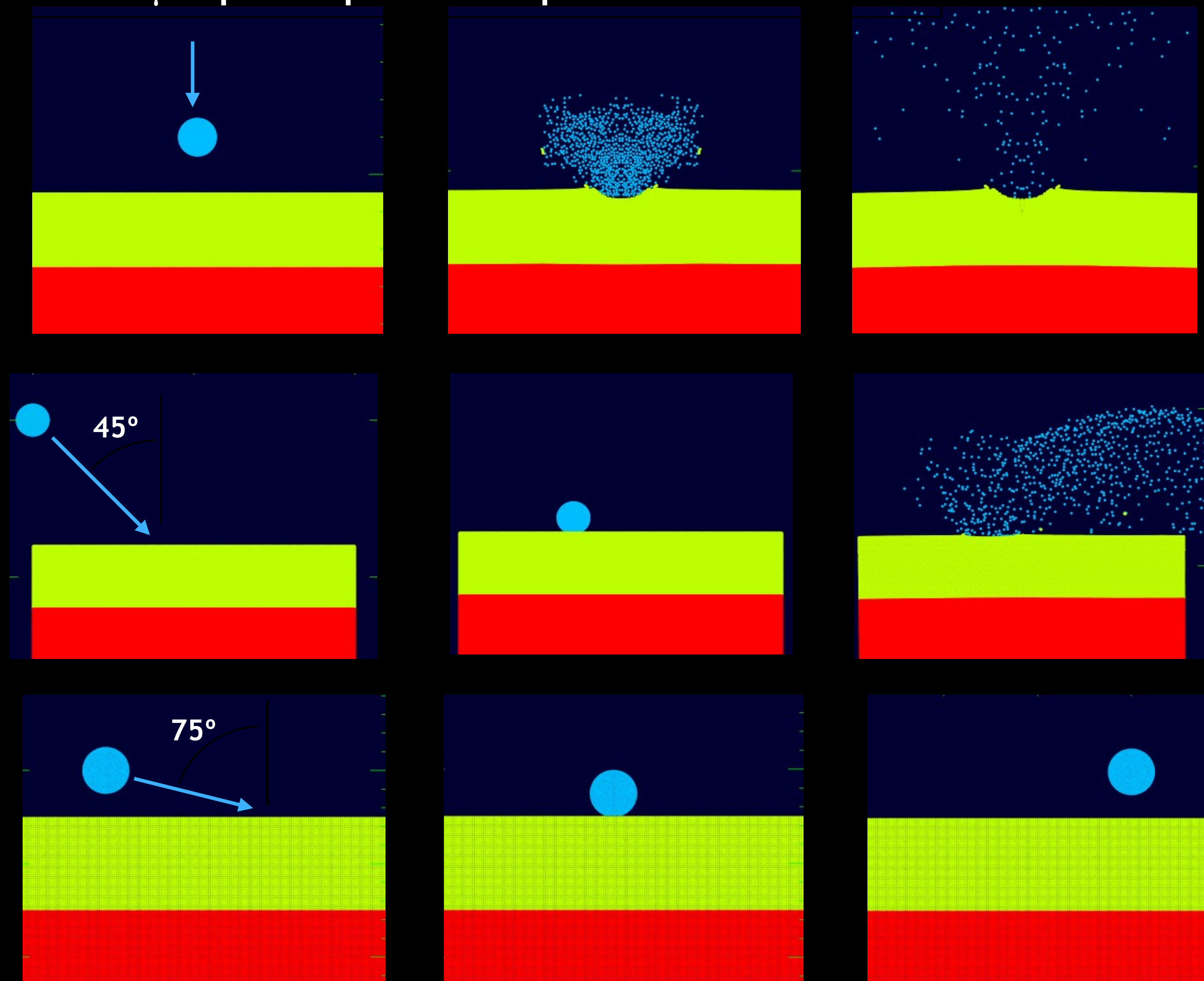
Liquid Phase Erosion

40 μm plume particle impact at 2 km/s

Normal Impact
[Damage]

45° Impact
[Damage]

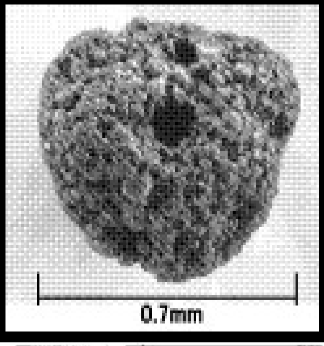
75° Impact
[No Damage]

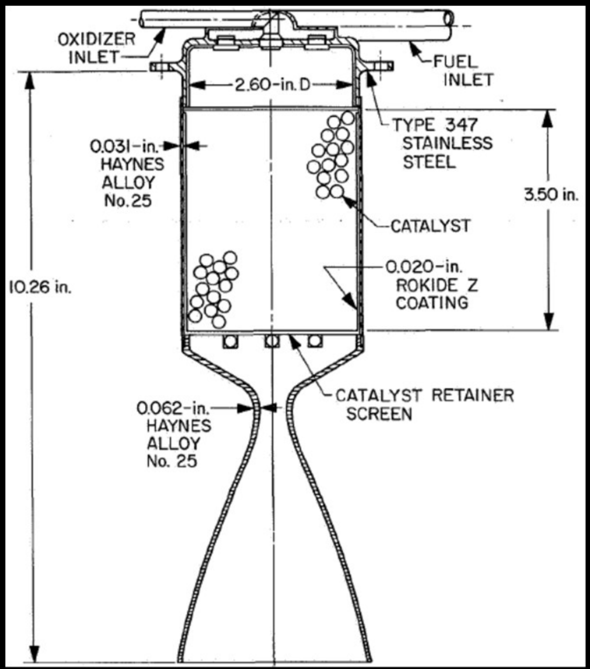


Source: Pankop, C., Alred, J., and Boeder, P.; “Mitigation of Thruster Plume-Induced Erosion of ISS Sensitive Hardware,” The 7th International Conference on “Protection of Materials and Structures from Space Environment, May 2004.

Solid Phase Contamination

- Solid-phase constituents can produce both contamination (permanent) and erosion (mechanical damage)
  - Discrete non-uniform deposits and erosion features (pitting)
  - Monopropellants (hydrazine): catalyst fine ejecta
  - Bipropellants (MMH/NTO): iron nitride particles
  - Contamination impacts to all missions with plume impingement on sensitive surfaces
- Engineering models have been developed (NASA) for use in the ISS Program

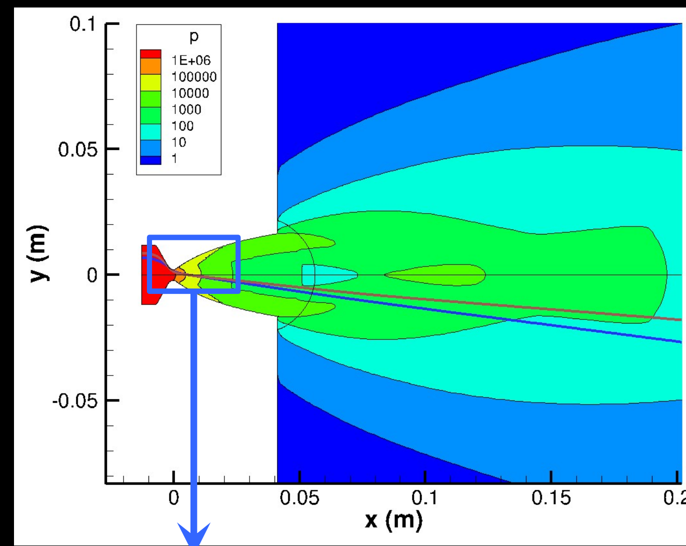


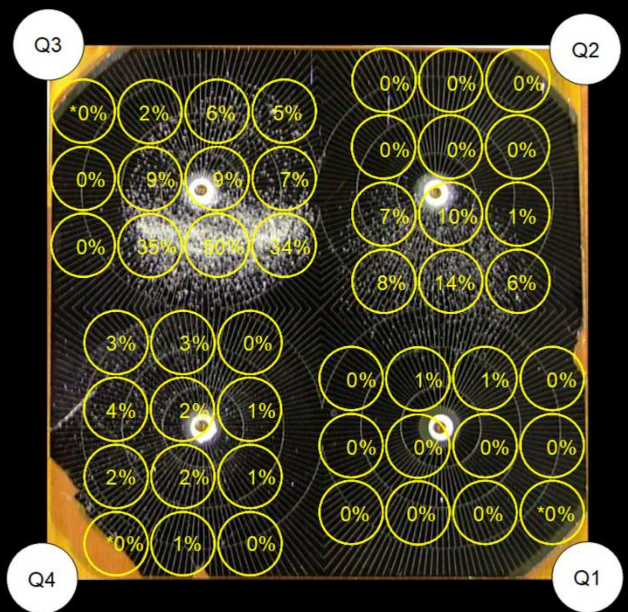


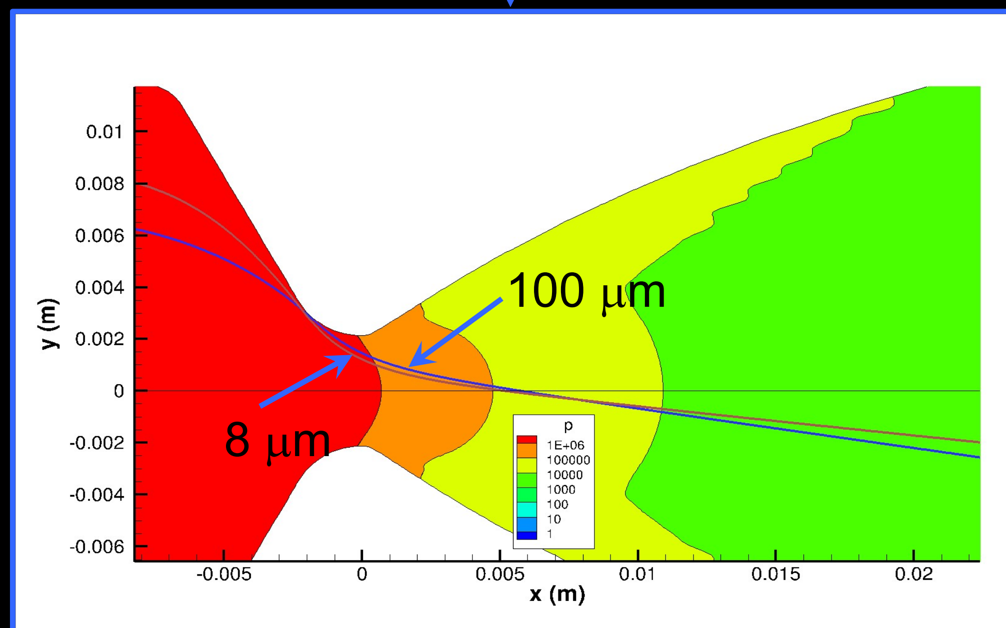
Source: Price, T.W., and Evans, D.D.; "The Status of Monopropellant Hydrazine Technology," NASA Technical Report 32-7227, February 1968.
Moynihan, P. I. and Bjorklund, R. A.; "Performance Characterization Tests of Three 0.44-N (0.7-lbf) Hydrazine Catalytic Thrusters," NASA Technical Report 32-7584, September 1973.
Goto, D., Kagawa, H., Hattori, A., & Kajiwara, K.; "Monopropellant Thruster Firing Test Using KC12GA Catalyst Monopropellant Thruster Firing Test using KC12GA Catalyst," Proceedings of the 3rd European Workshop on Hydrazine (ESA SP-556), June 2004.

Solid Phase Erosion

- Monopropellants thrusters (hydrazine) produce catalyst fine ejecta (aluminum oxide/iridium) that can impact spacecraft surfaces near plume centerline
- Engineering models have been developed (NASA) for use in the ISS Program





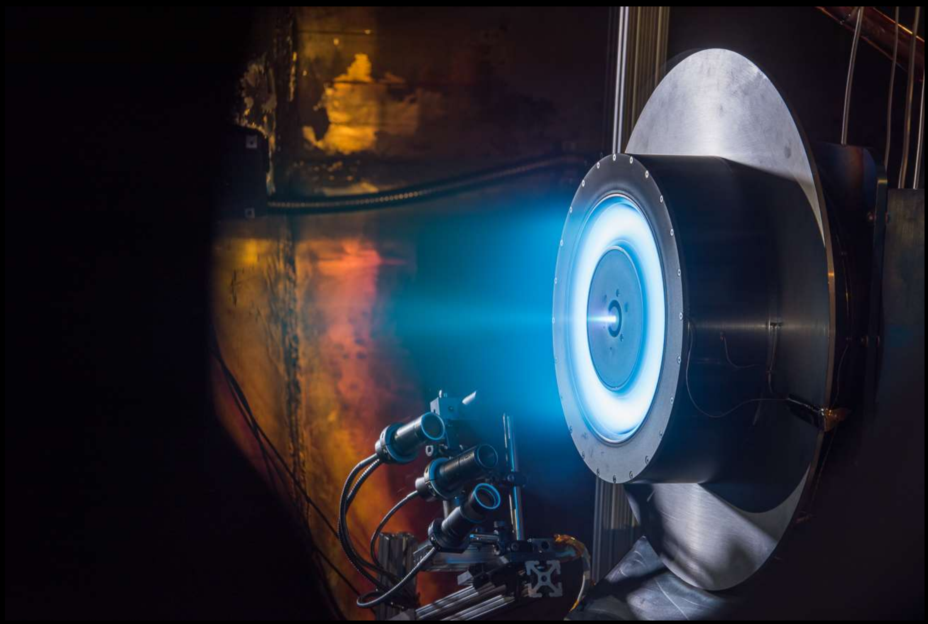


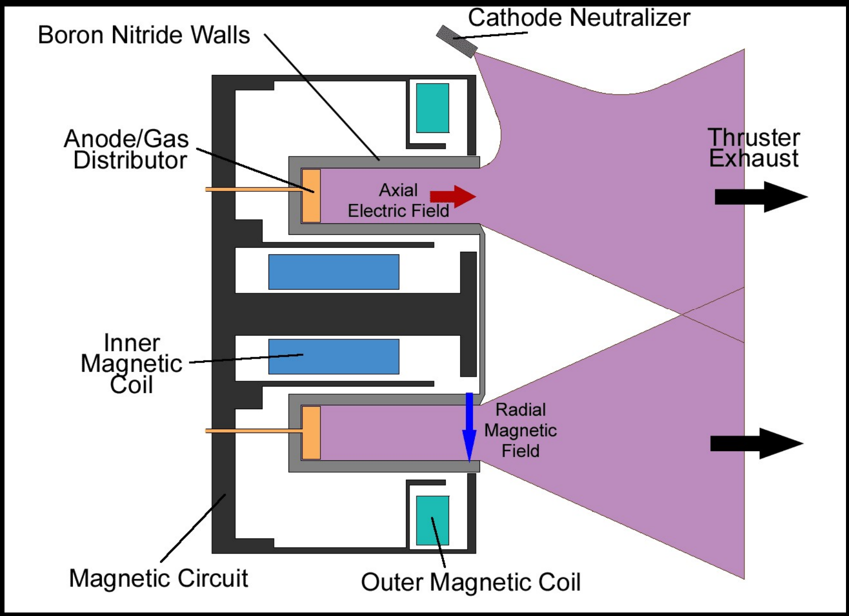
Source: Larin, M., Lumpkin, F., and Stuart, P.; "Modeling unburned propellant droplet distribution and velocities in plumes of small bipropellant thrusters", 35th AIAA Thermophysics Conference, AIAA 2001-2816, 2001.

Electric Propulsion Induced Contamination

- Plume constituents:
  - Ionized gas: Xe
  - Neutrals: boron nitride
- High performance (Isp)
- High ionized gas plume velocities

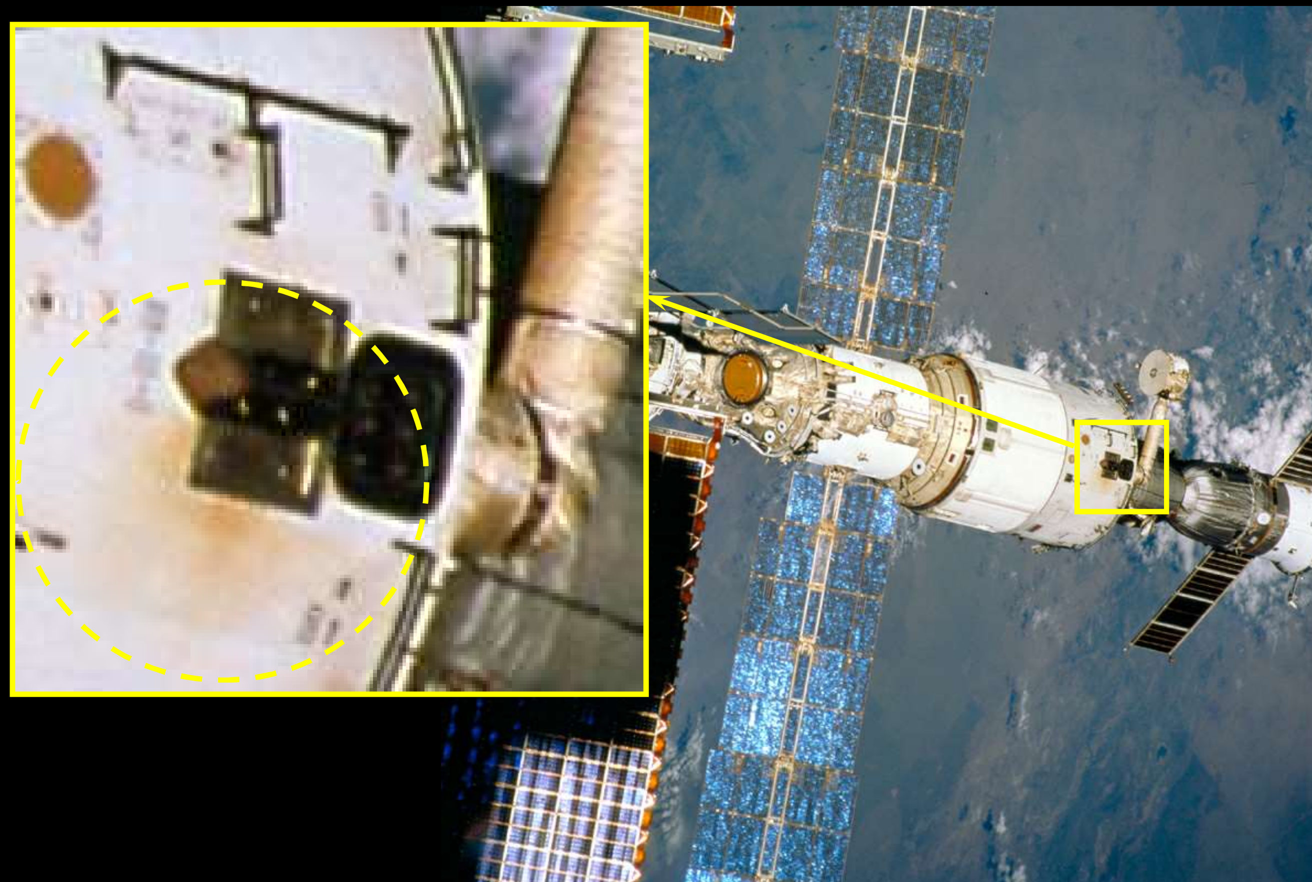
- Contamination concerns: optical property degradation from boron nitride deposition on contamination sensitive spacecraft systems and science inctruments





Source: Trevisani, L., Negrini, F., & Martinez-Sanchez, M.; "Material Deposition Measurements from a Hall Thruster using a Quartz Crystal Microbalance,' Proceedings of the 4th International Spacecraft Propulsion Conference (ESA SP-555), June, 2004.

ISS plume induced contamination and erosion model development and application

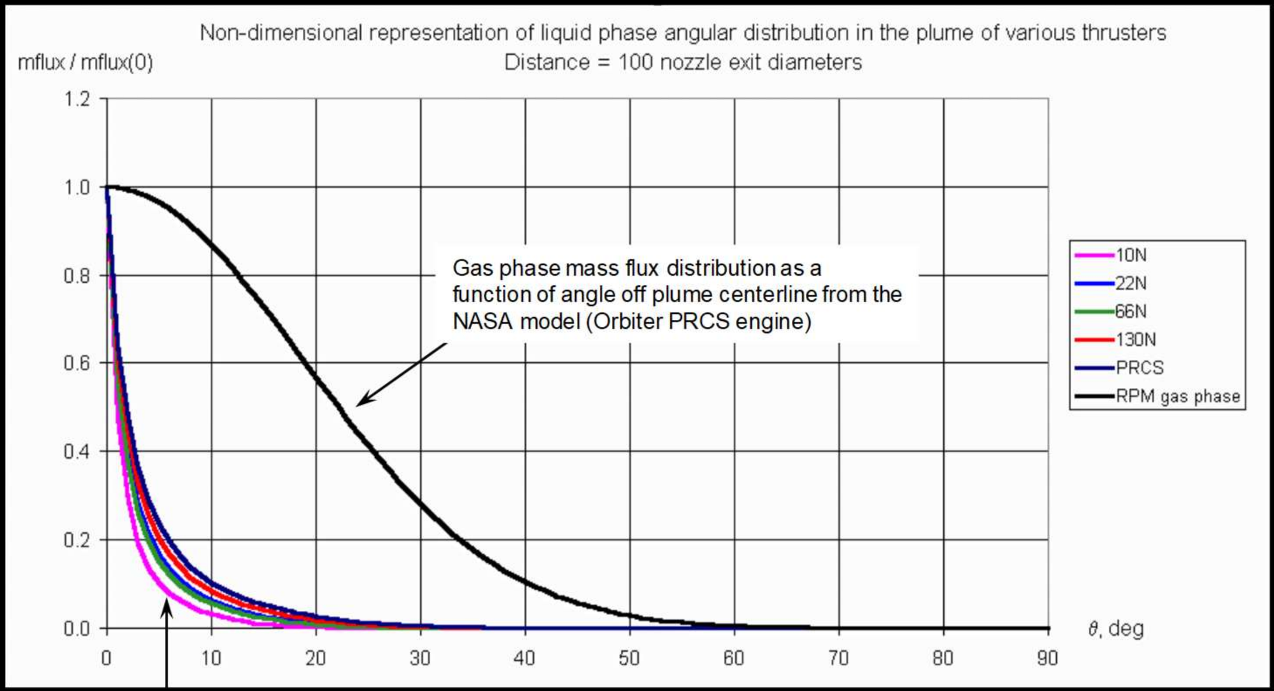


- Supporting chamber data used in the ISS model development
- Supporting flight experiment data - NASA SPIFEX and PIC plume induced contamination experiments and on-orbit measurements
- Erosion testing and modeling (high-velocity impact testing and modeling with SPH hydrocodes)
- Application of the engineering models to ISS, Shuttle and ISS visiting vehicles
    - Solar array erosion
    - EVA considerations: composition and toxicity of plume contaminant deposits

Image source: NASA/JSC

Supporting Chamber and On-Orbit Data (ESA/DLR-Trinks, U.S. and Russian) Used in the ISS Plume Model Development

	MBB	*MBB*	*Kaiser-Marquardt*	*Aerojet*	*Russian*	*PRCS*
Model	S4 / (SK1016)	(SKA795)	R6D / (R6C).	AJ10-220	11D428A-16	F3U
Thrust (N)	5	10	22	66	130	3870
Thrust (kg)	0.51	1.02	2.24	6.73	13.3	394
Thrust (lbf)	1.12	2.24	4.95	14.8	29.2	870
Fuel	MMH/MON-1	MMH/MON-1	MMH/MON-3	MMH/NTO	UDMH/NTO	MMH/NTO
R_{exit} (mm)	15	18.5	25.4	35.28	43.65	94.72
Pulse Width (ms)		40/80			100	80



NASA PIC and SPIFEX Flight Experiments

- NASA obtained on-orbit thruster plume induced contamination measurements from the PIC (Plume Impingement Contamination) and SPIFEX (Shuttle Plume Impingement Flight Experiment) flight experiments
- SPIFEX was flown on Space Shuttle mission STS-64 in 1994.
  - Contamination measurements of molecular deposition were made by XPS (X-ray Photo Spectroscopy)
  - Droplet impact features were also recorded with SEM (Scanning Electron Microscope) scans on Kapton and aluminum foil substrates
- PIC was conducted during STS-74 in 1996
  - Quartz Crystal Microbalances (QCMs) measured contaminant deposition from U.S. and Russian thruster firings
  - Droplet impact observations were made with SEM scans of the Shuttle RMS (Remote Manipulator System) camera lens
- These flight experiments were successful in providing measurements of plume induced contamination as well as droplet impact damage

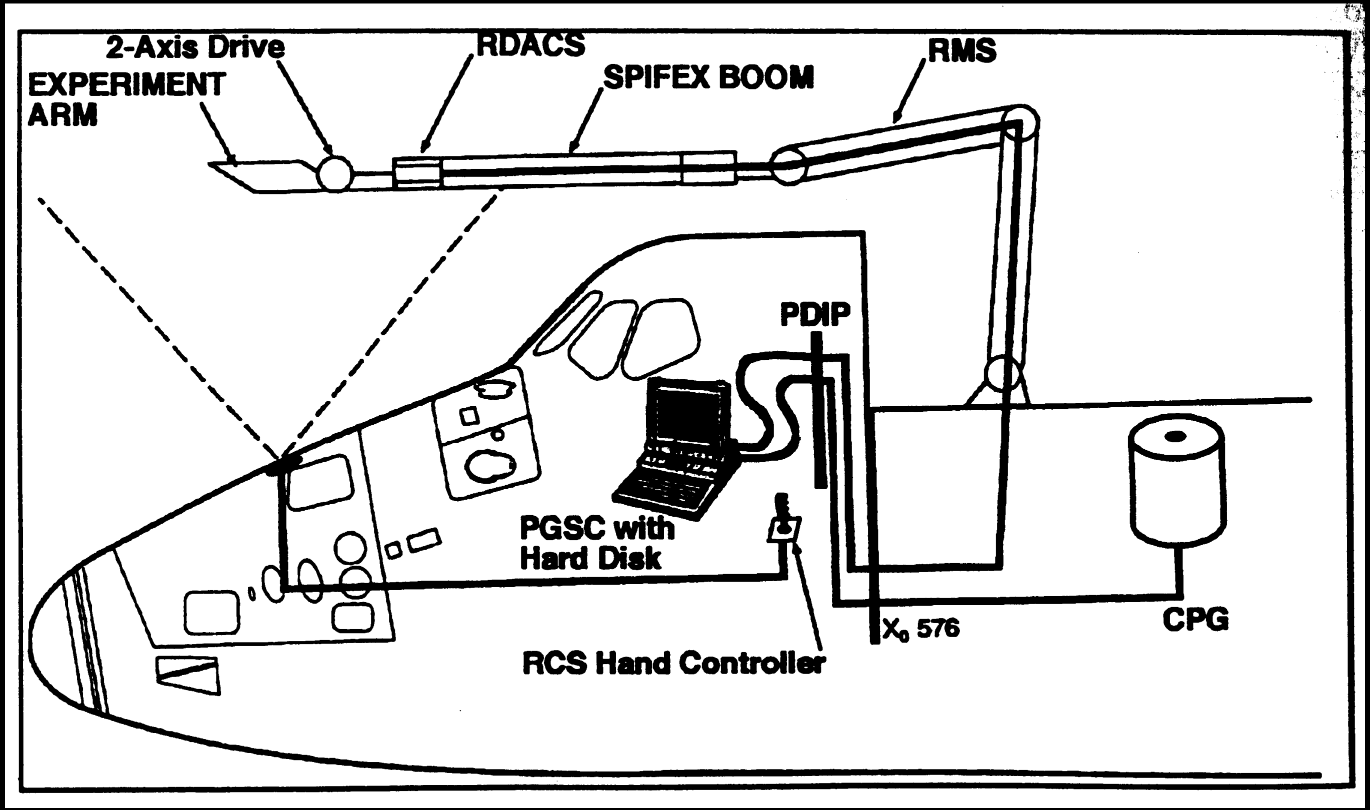
Source: Soares, C. and Mikatarian, R., "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments", SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

Shuttle Plume Impingement Flight Experiment (SPIFEX)

- Purpose: to produce measurements of plume impingement forces, heating effects, static/dynamic pressures and plume induced contamination
- Flown on STS-64 in September 1994
- Both Shuttle Primary Reaction Control System (PRCS) and Vernier Reaction Control Systems (VRCS) engines were fired:
  - 84 PRCS and 17 VRCS firings with pulse widths ranging from 80 to 720 milliseconds
  - Distances varied from 8 to 76 feet
  - Angles off-plume centerline varied from 0 to 90°
- Materials witness coupons (aluminum and Kapton) were used in the characterization of permanent plume induced contamination and droplet impact features

Source: Soares, C. and Mikatarian, R., "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments", SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

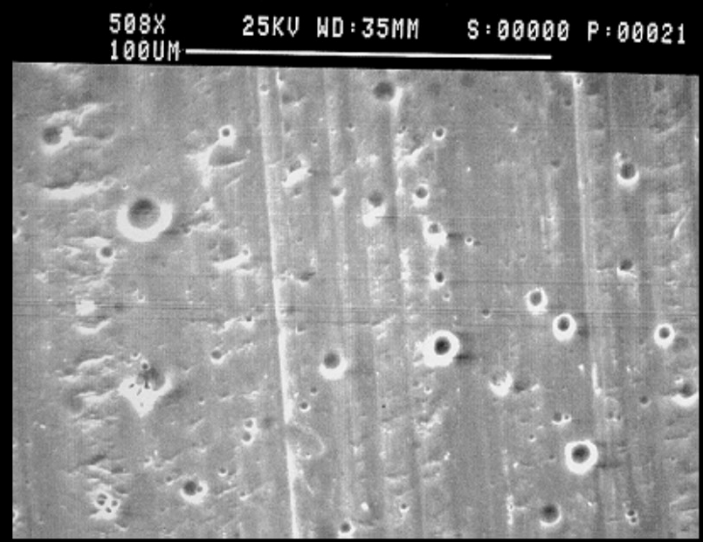
Shuttle Plume Impingement Flight Experiment (SPIFEX)

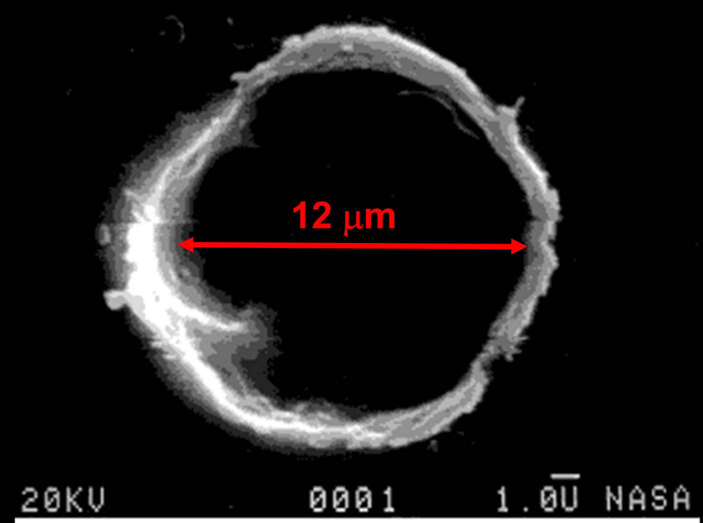


Source: Soares, C. and Mikatarian, R., "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments", SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

SPIFEX Analysis - Aluminum Coupons

- **Droplet impact craters observed on Aluminum witness coupons**
- **Crater sizes: 1-20 μm in diameter (not visible to unaided eye**
- **Chemical analysis showed nitrates as well as Fe and Cr**
- **From analysis of SEM photos, 740 impacts/mm^2 observed**
- **Pitted area represents ~ 4.1% of the surface area of coupon (result of 101 pulses)**





SPIFEX

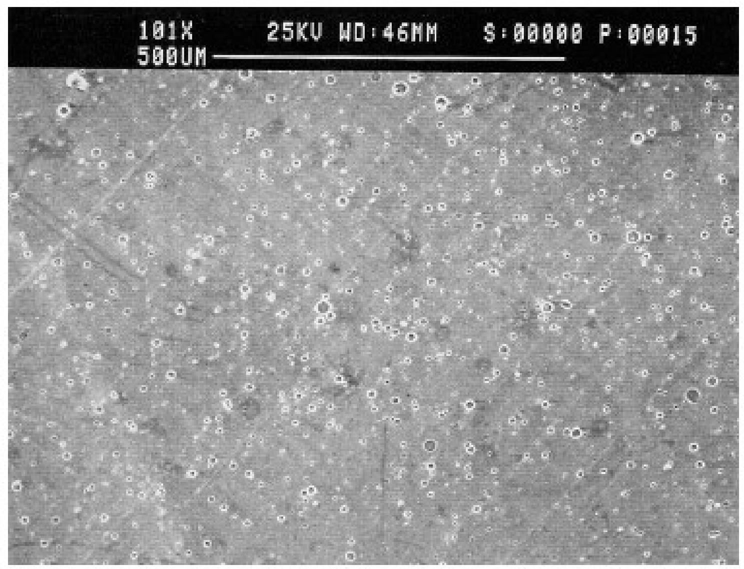
Small Pits	≤ 4 μm	449
Medium Pits	5-10 μm	231
Large Pits	11-20 μm	60

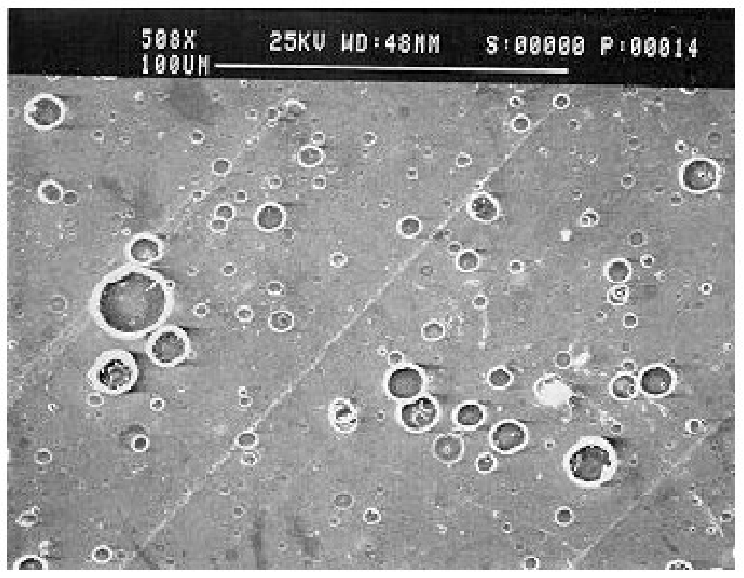
Source: Soares, C. and Mikatarian, R., "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments", SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

SPIFEX Analysis - Kapton Tape

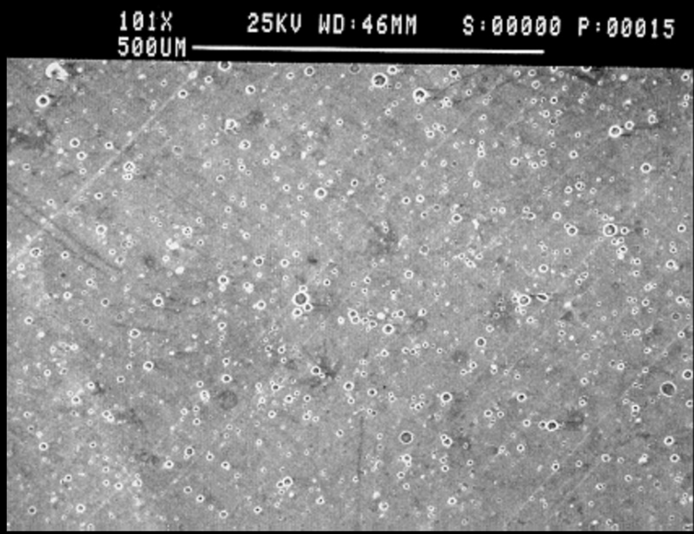
- Craters on the Kapton tape are the result of impingement of chemically reactive liquid drops
- MMH dissolves Kapton and other polyimides
- Crater sizes: 1-40 μm in diameter (not visible to unaided eye)
- From analysis of SEM photos, 2,200 impacts/mm^2 observed on Kapton tape samples
- Pitted area represents ~ 10% of the surface area of coupon (result of 101 pulses)

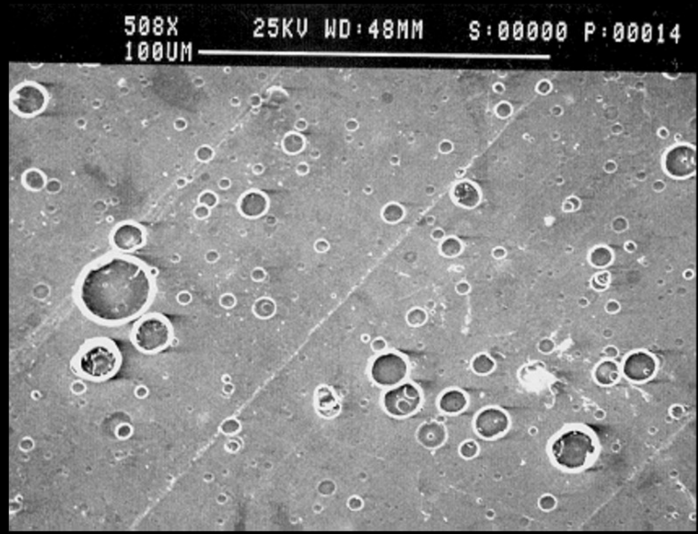
Source: Soares, C. and Mikatarian, R., “Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments”, SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

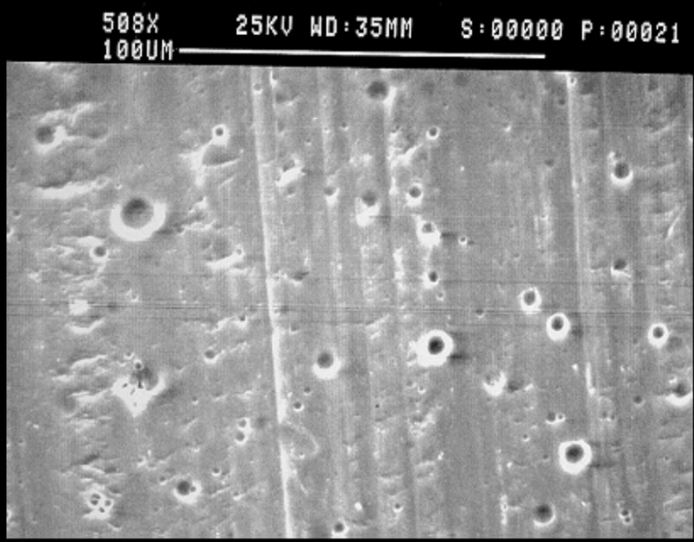


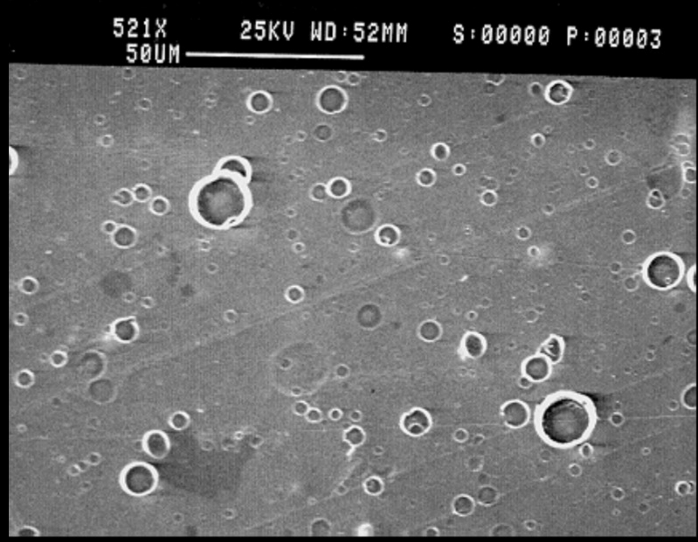


SPIFEX
Features from Droplet Impacts





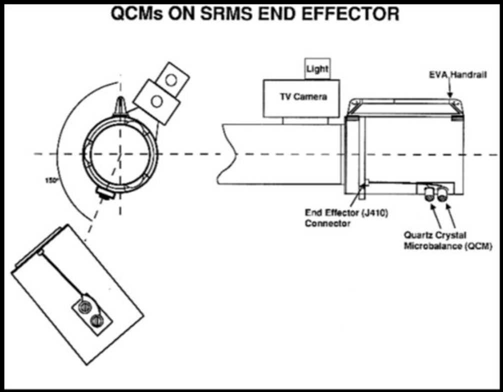




Source: Soares, C. and Mikatarian, R., "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments", SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

Plume Impingement Contamination (PIC) Flight Experiment

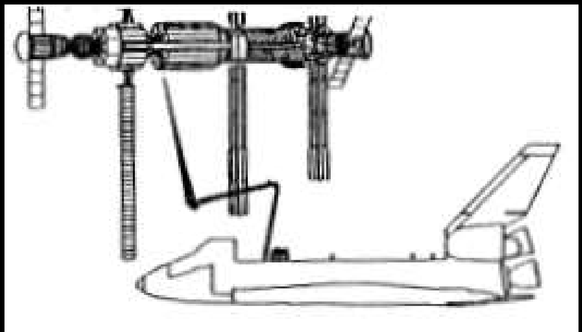
- Purpose: to measure initial and permanent plume induced molecular contamination produced by the Orbiter PRCS (F3U) and Russian 130 N (model 11D428A-16) thrusters
- Flown on STS-74 in November 1995 (DTO-829)
- PIC provided critical data on plume induced contamination from the Orbiter PRCS (F3U) and the Russian 130 N thruster (model 11D428A-16) used on the Mir space station
- QCMs were used to determine mass deposition for each thruster tested
- PIC QCM measurements for the Orbiter PRCS and Russian 130 N thrusters were made only on the plume centerline, for QCM temperatures in the range of 298 K



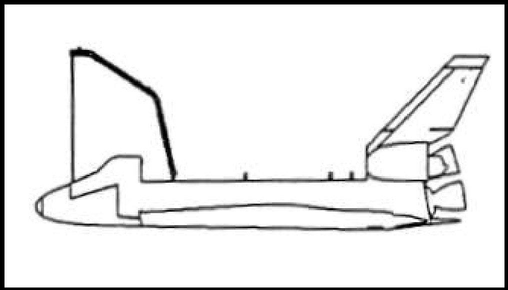
Source: Soares, C. and Mikatarian, R., “Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments”, SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

The Plume Impingement Contamination (PIC) Flight Experiment

- Orbiter PRCS thruster measurements were taken for two groups of ten 80 millisecond pulses (total of 20 pulses with a total on-time of 1.6 seconds), on plume centerline, at a distance of 34.7 feet. The QCM was canted at an angle of 35° with respect to the centerline flux stream.
- Russian 130 N thruster measurements were made for ten sets of ten 100 millisecond pulses (total of 100 pulses with a total on-time of 10 seconds, on plume centerline, at a distance of 40 feet.



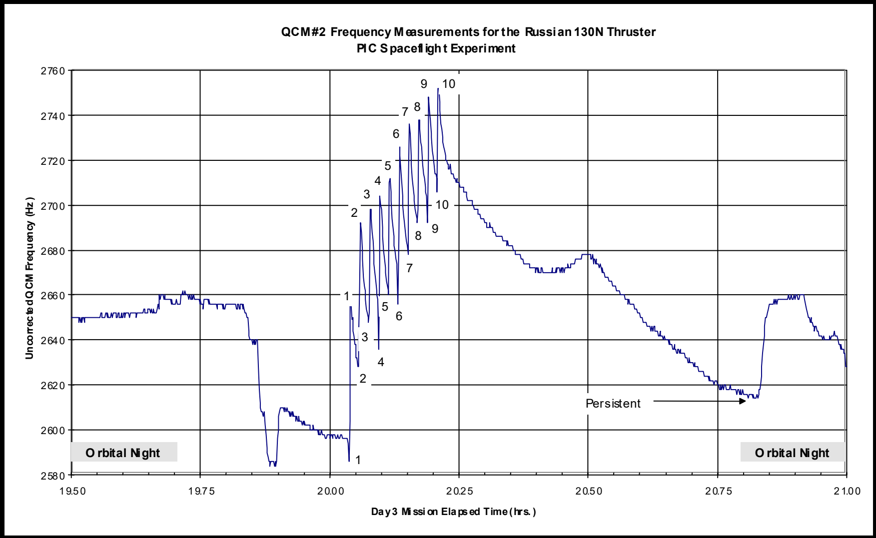
Russian 13 kg Firing

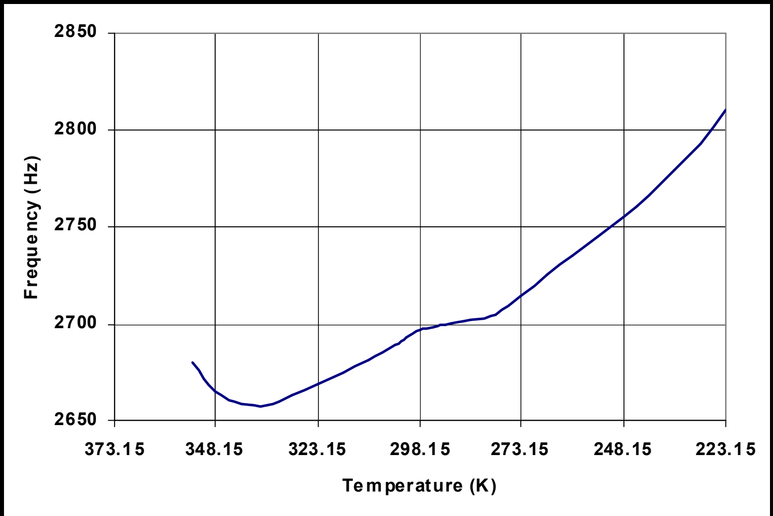


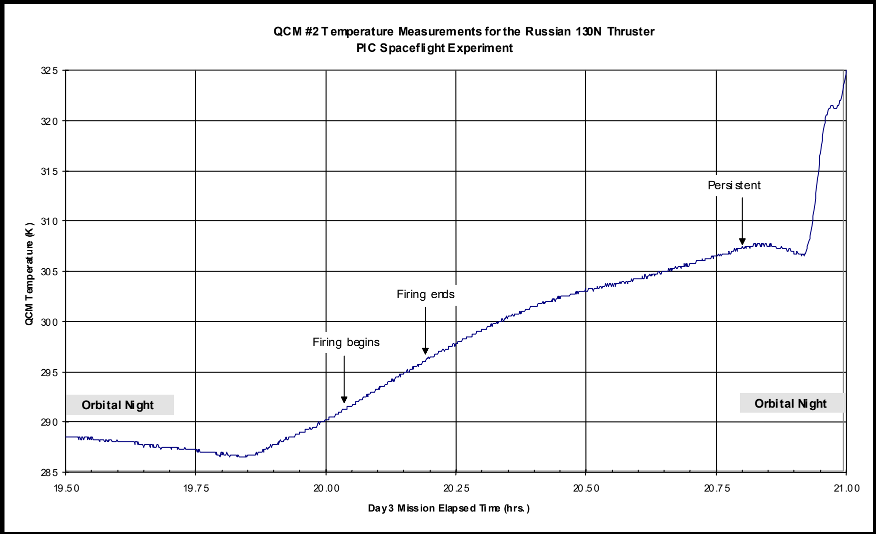
Source: Soares, C. and Mikatarian, R., "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments", SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

PIC Results for the Russian 130 N Thruster (model 11D428A-16)

- Data files from PIC show QCM frequency and temperature versus mission elapsed time (MET) at a distance of 12.2 m



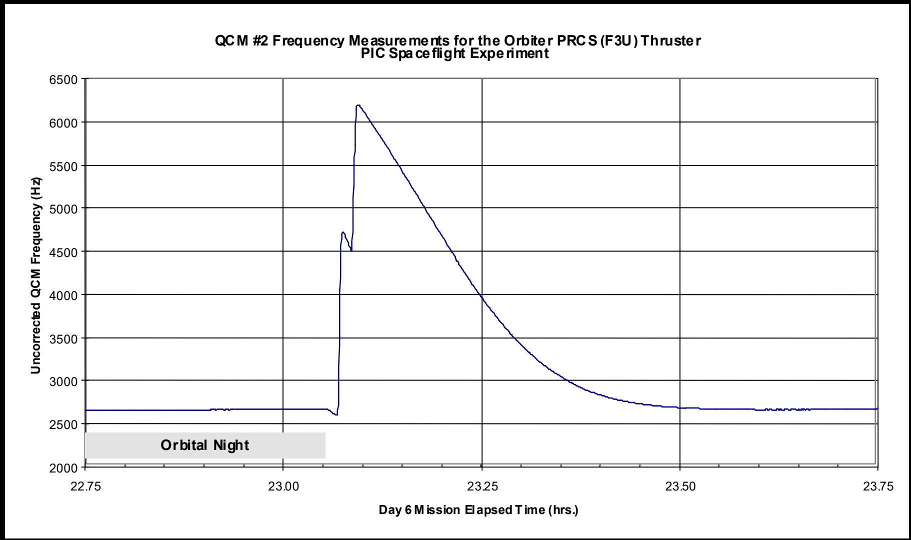


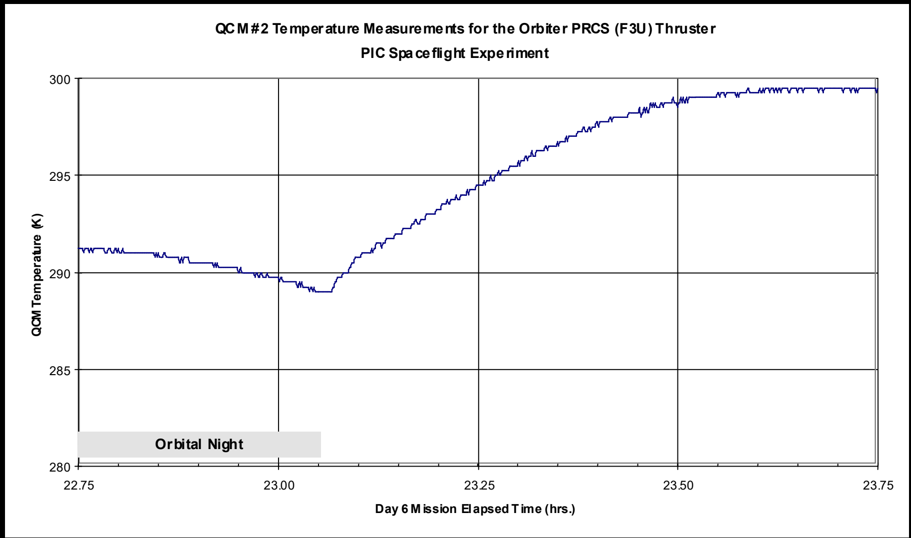


Source: Soares, C. and Mikatarian, R., "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments", SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

PIC Results for the Orbiter PRCS Thruster (F3U)

- PIC also measured contaminant deposition from the Orbiter F3U PRCS thruster, with a rated thrust of 870 lbf (3870 N)
- For the PRCS measurements, the QCMs were placed at a distance of 10.58m from the nozzle exhaust plane, on the plume centerline
- The incidence angle between the plume mass flux vector and the QCM active surface was 35°
- The firing history consisted of two groups of ten 80 ms pulses, with a 45 second rest between the two groups, for a total thruster on time of 1.6 seconds

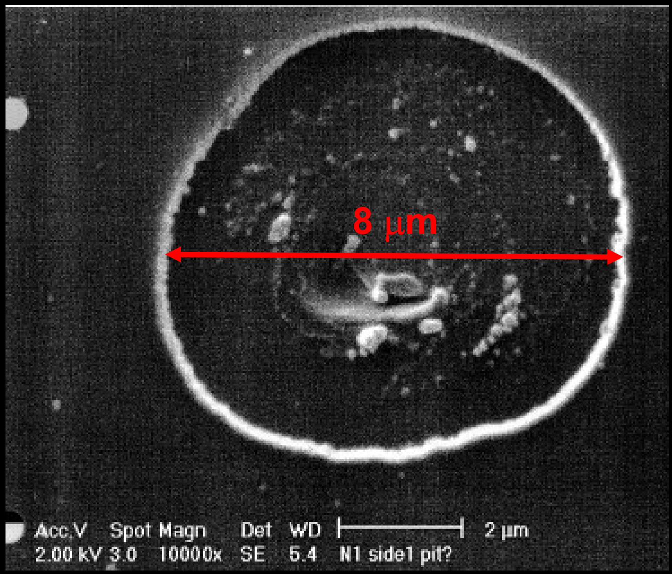




Source: Soares, C. and Mikatarian, R., "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments", SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

PIC Analysis

- **PIC Camera Lens (fused silica) shows impact craters not visible to unaided eye.**
- **From analysis of SEM photos, 61 impacts/mm^2 observed.**
- **Pitted area represents ~ 1.8% surface area of camera lens (result of 120 pulses).**

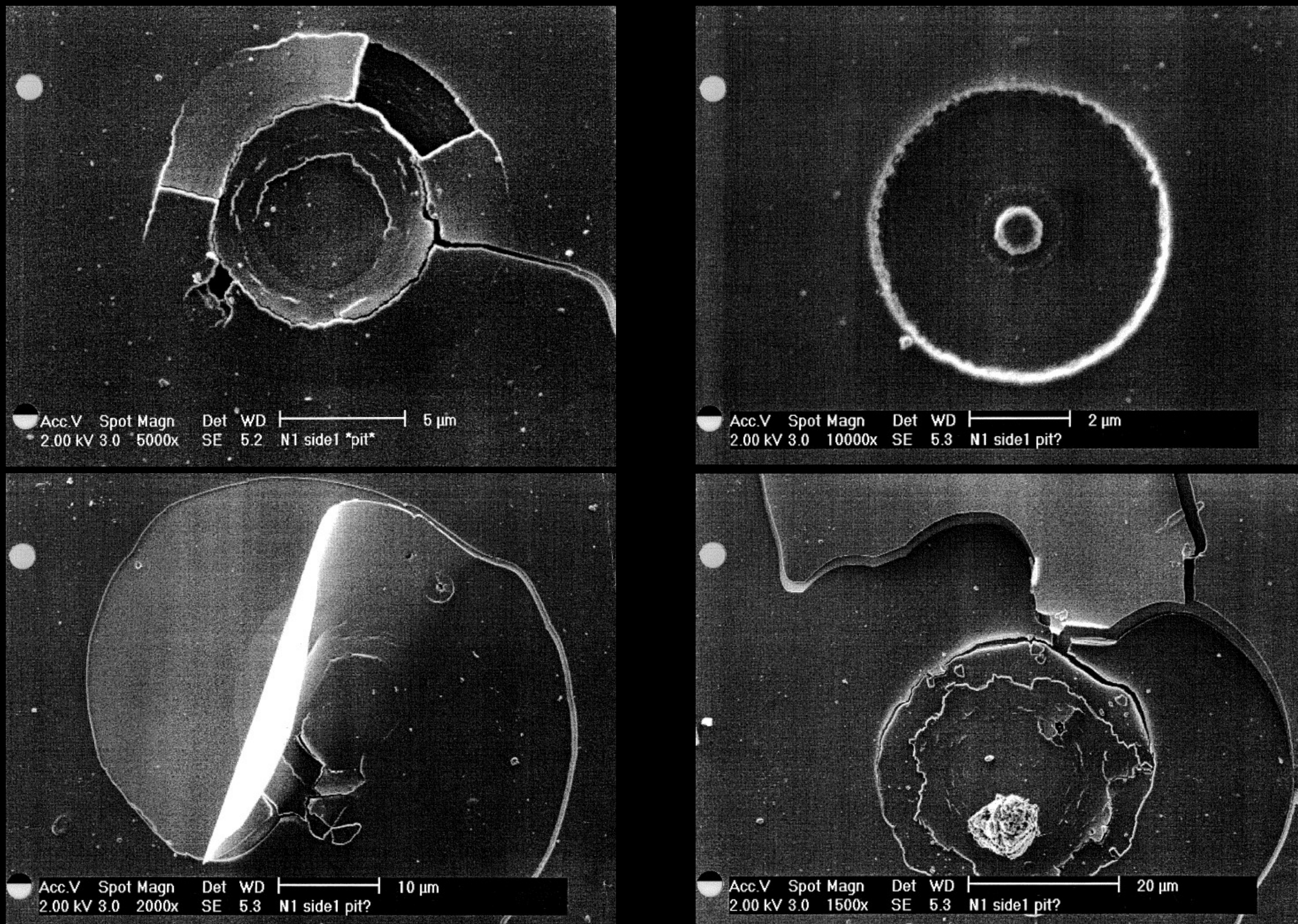


PIC Camera Lens

Small Pits	2-5 μm	21	17790
Medium Pits	6-13 μm	30	25830
Large Pits	14-24 μm	10	8895

Source: Soares, C. and Mikatarian, R., "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments", SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

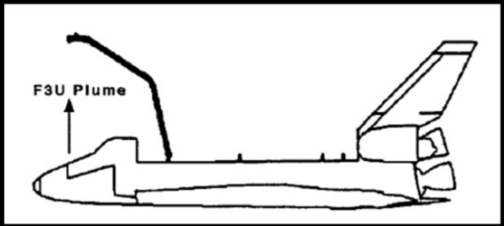
Impact Features on the PIC Camera Lens

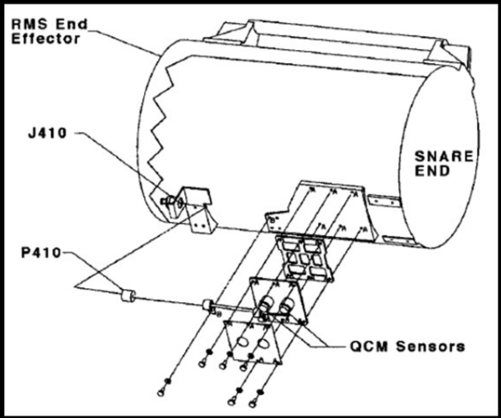


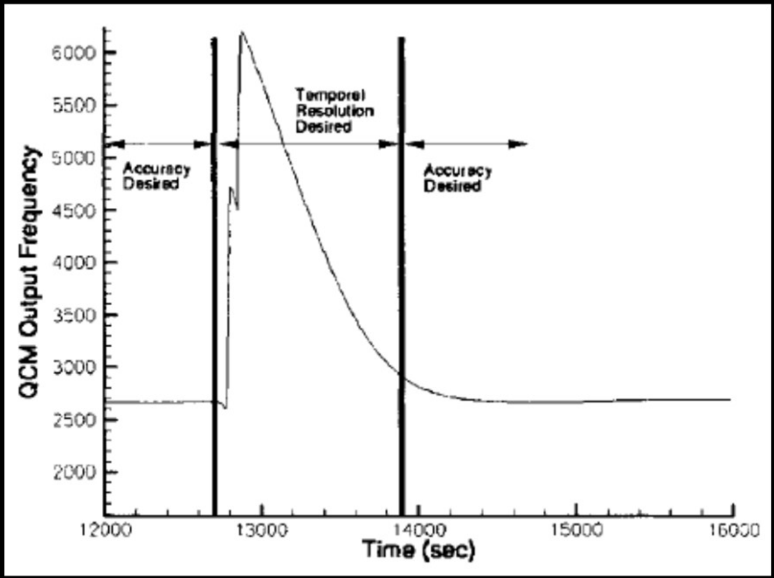
Source: Soares, C. and Mikatarian, R., “Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments”, SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

PIC II Flight Experiment

- The Plume Impingement Contamination II (PIC II) flight experiment was designed (and built) as a follow-on to the PIC flight experiment
    - PIC II was designed with more sensitive temperature controlled QCMs, to characterize the angular distribution of contaminant mass flux in the plume of the Orbiter PRCS thruster



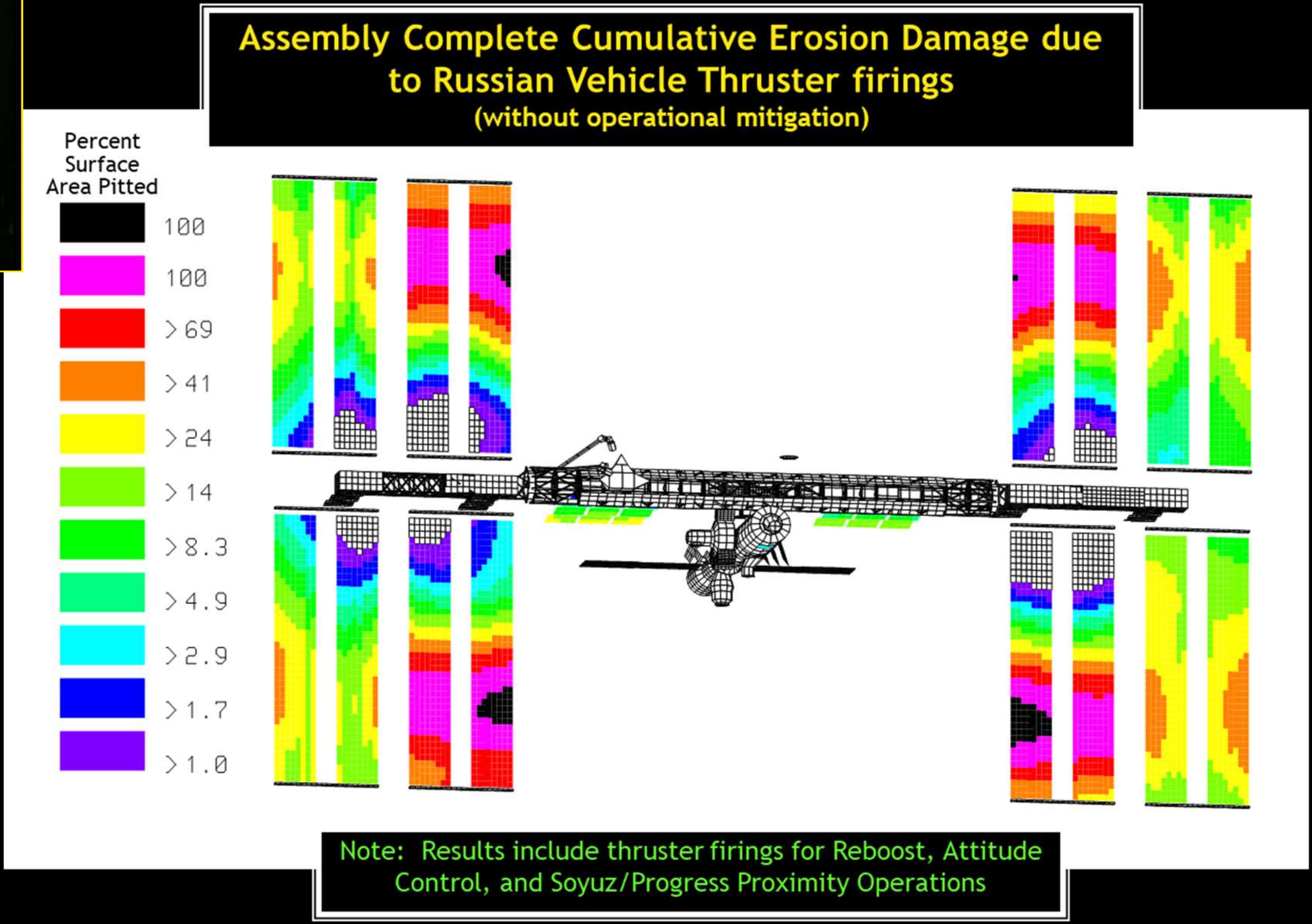




Source: Lumpkin, F.E., Albyn, K.C. and Farrell, T.L., "The Plume Impingement Contamination II Experiment: Motivation, Design and Implementation Plan," AIAA 2001-2815, 35th AIAA Thermophysics Conference, June 2001.

Plume Erosion Mitigation

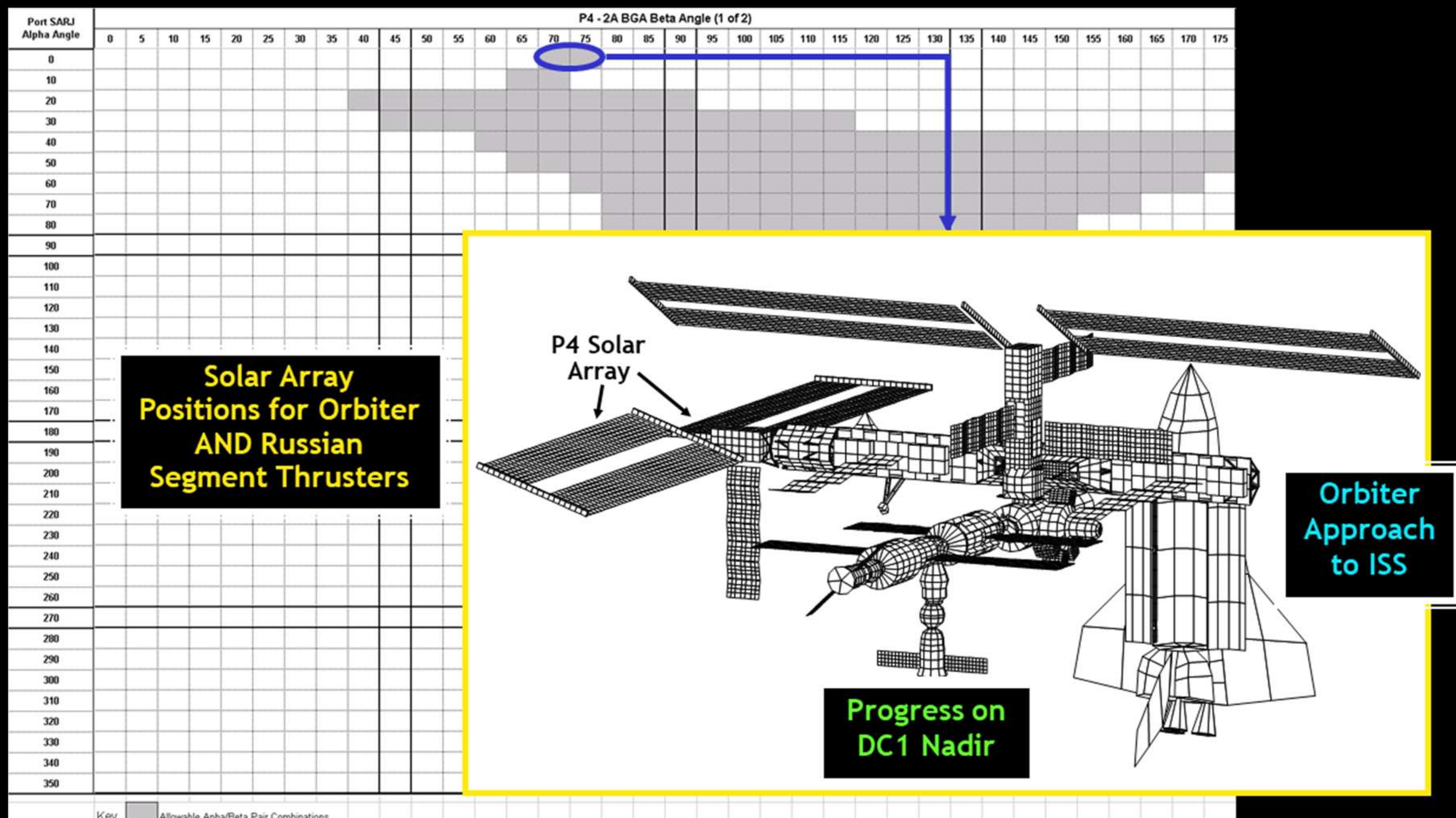
Exhaust Plume of an Orbiter Primary Reaction Control System Thruster



Source: Pankop, C., Alred, J., and Boeder, P.; "Mitigation of Thruster Plume-Induced Erosion of ISS Sensitive Hardware," The 7th International Conference on "Protection of Materials and Structures from Space Environment, May 2004.

Plume Erosion Mitigation
Example Table for Allowable ISS Solar Array Positions

- Example table shows allowable ISS P4 Solar Array alpha/beta pair combinations which mitigate plume erosion due to Orbiter Approach Proximity Operations



Source: Pankop, C., Alred, J., and Boeder, P.; "Mitigation of Thruster Plume-Induced Erosion of ISS Sensitive Hardware," The 7th International Conference on "Protection of Materials and Structures from Space Environment, May 2004.

Plume Induced Contamination and Erosion for Deep-Space and Planetary Missions – Detection of Organics and Life

- Potential impacts to the detection of organics and life detection
- Mars 2020 plume contamination (rover mission)
- Europa Clipper plume contamination and erosion (orbiter mission)
- Europa Lander (lander mission concept)
- Mars Sample Return mission (concept)

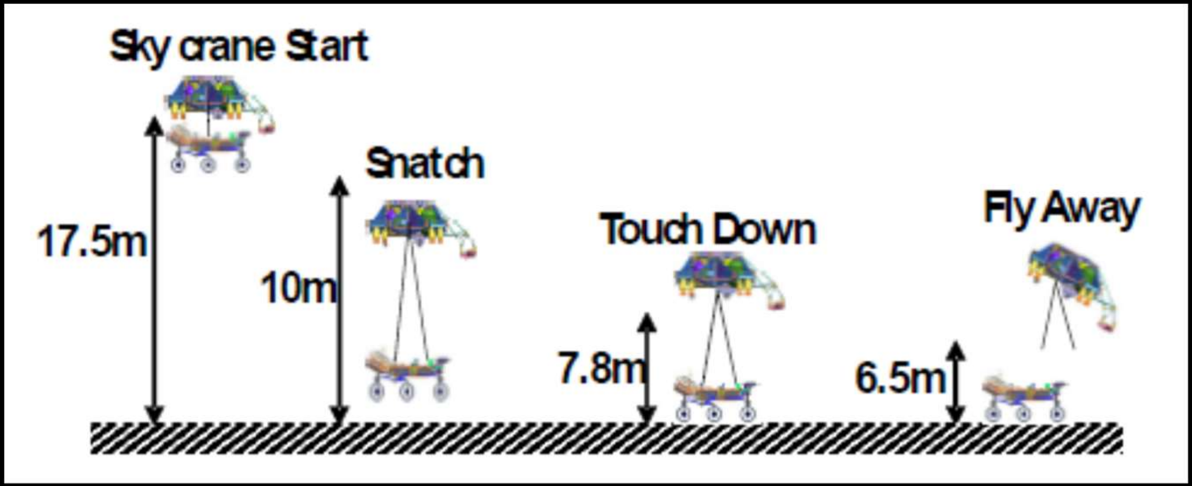
Image source: JPL/Caltech

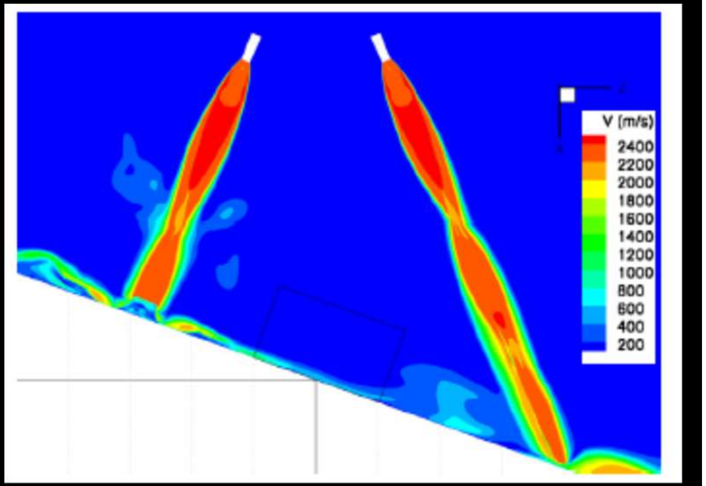
Potential Impacts to the Detection of Organics and Life Letection

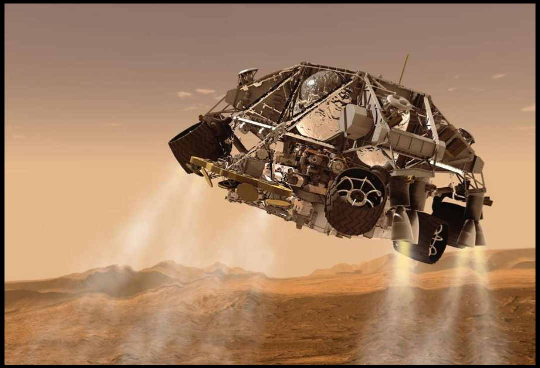
- Thruster operations produce contamination that can affect science instruments for orbiter, lander and rover missions
- Organic compounds in the both monopropellant and bipropellant plumes can produce contamination of science instruments on orbiters, lander and rovers, and also contaminate landing sites
  - Contamination of planetary surfaces during landing operations are of particular importance to landers since they will not move away from the landing site
- In addition to contamination, thruster plumes can induce erosion (mechanical damage) to spacecraft surfaces and instruments
  - Catalyst fine ejecta and droplets in monopropellant hydrazine thrusters
  - Droplets and iron nitride particles in bipropellant thrusters (MMH/NTO and UDMH/NTO)

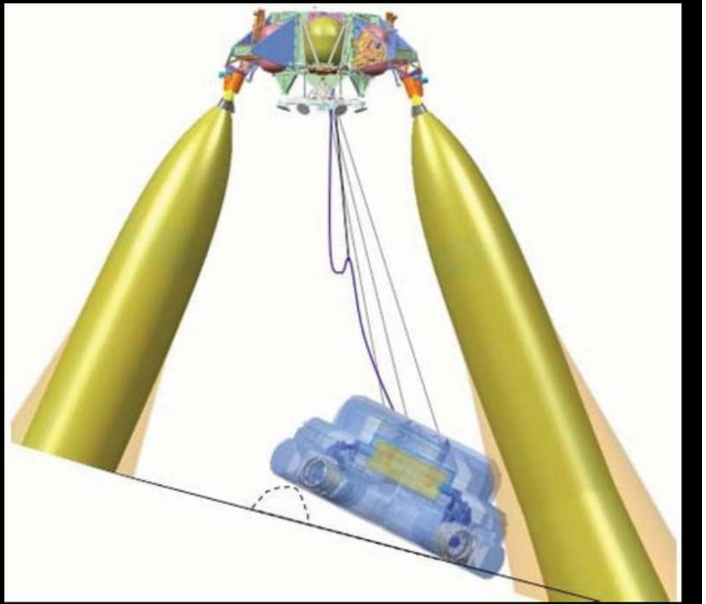
Source: Lumpkin, F.E., Albyn, K.C. and Farrell, T.L., "The Plume Impingement Contamination II Experiment: Motivation, Design and Implementation Plan," AIAA 2001-2815, 35th AIAA Thermophysics Conference, June 2001.

Mars 2020 Plume Contamination









Source: Senguta, A., et al, “Mars Lander Engine Plume Impingement Environment of the Mars Science Laboratory,’ IEEE, 2008
Summons, R.E., et al, “Planning Considerations Related to the Organic Contamination of Martian Samples and Implications for the Mars 2020 Rover,” 2014.
http://www.spaceflight101.net/msl-landing-special.html

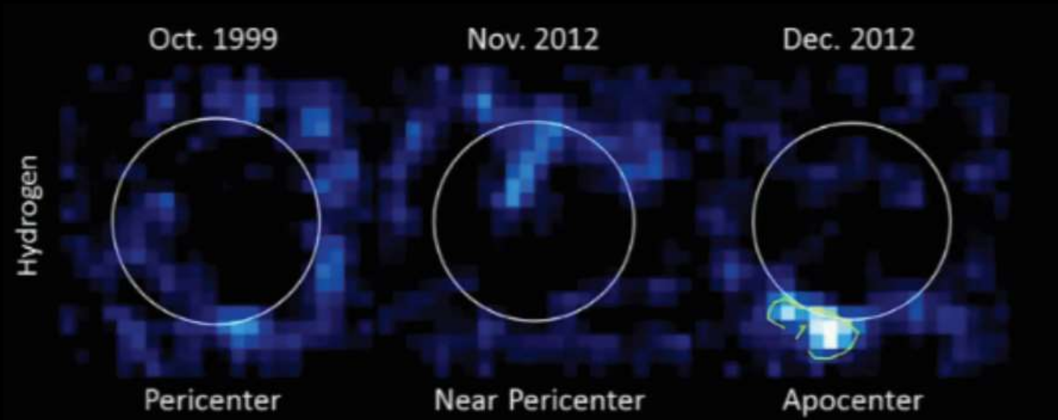
Image source: NASA/JPL

Europa Clipper

Europa Clipper (Orbiter)

Mission in Phase B – Preliminary Design

- *Orbiter will have a high-sensitivity mass spectrometer to measure composition of Europa plumes*
- *Modeling interactions of Europa exosphere and plumes with orbiter thruster plumes (and materials outgassing)*



Hubble Ultraviolet images showing signs of plumes near Europa's south pole. [visible-light image of Europa has been added as a visual aid]

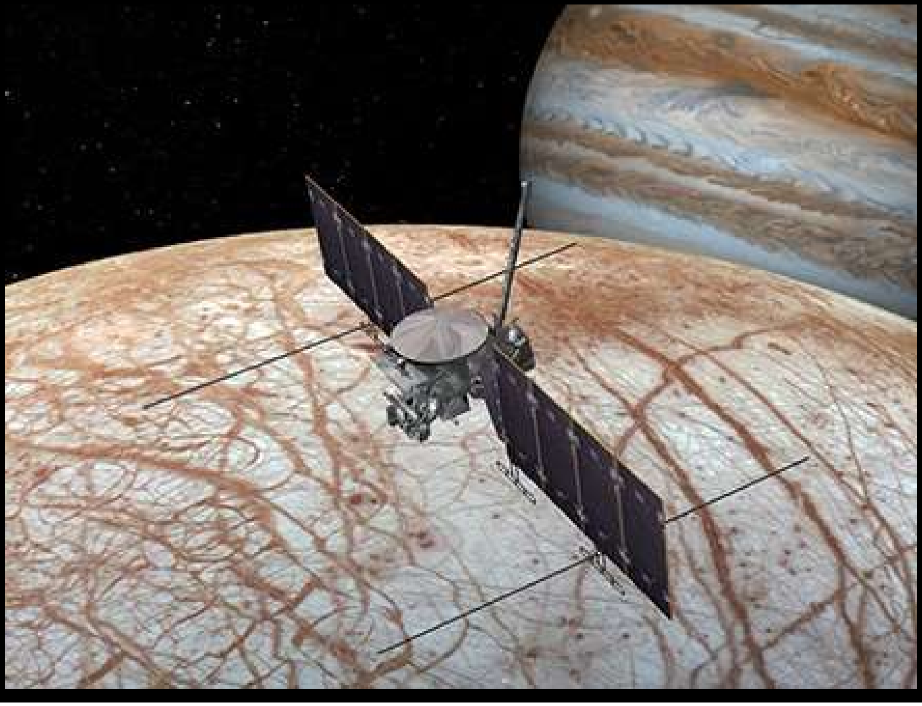


Image source: NASA/JPL

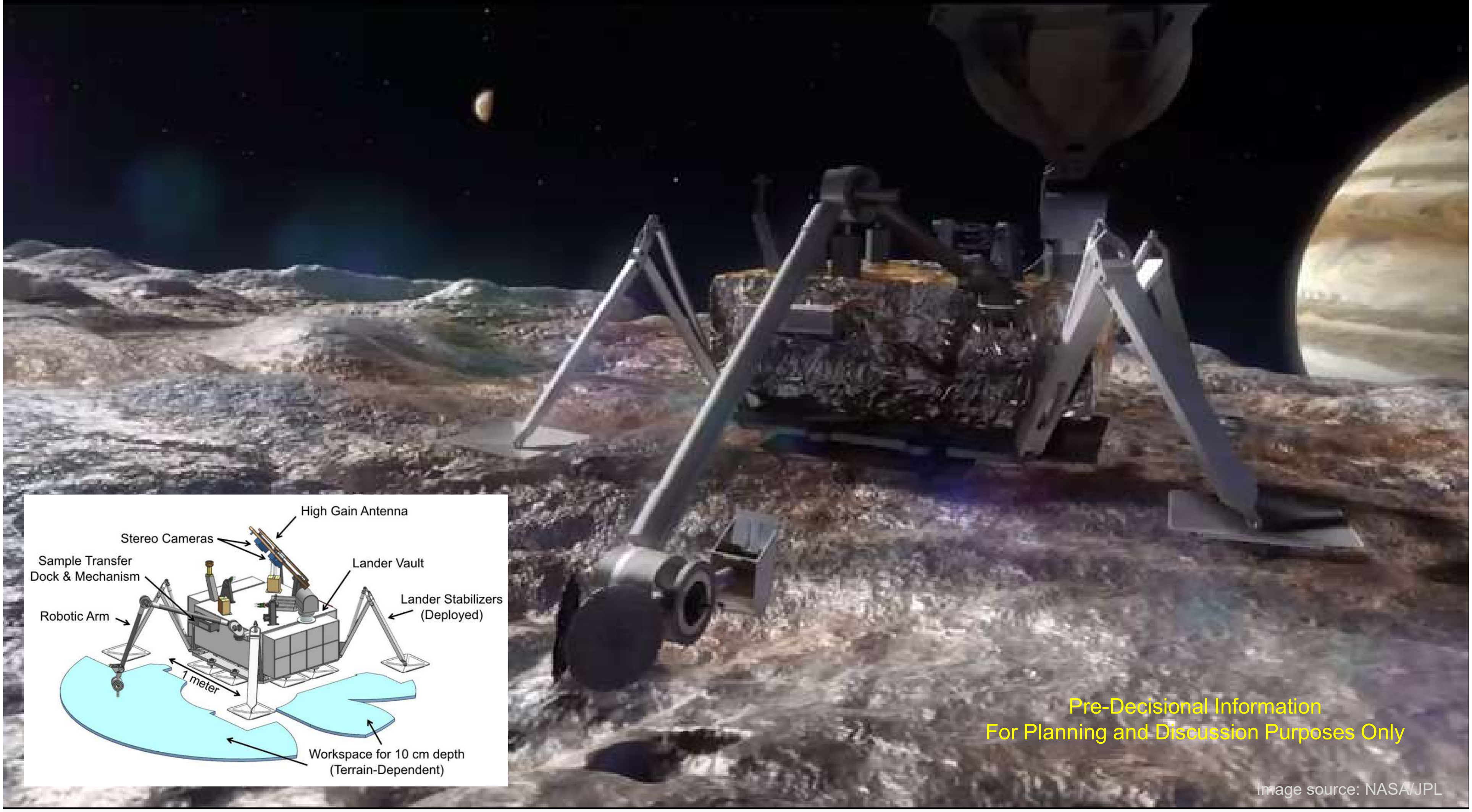
Europa Lander Concept

Europa Lander (lander mission concept)

Mission in Phase A

Mission Concept Review (MCR): March 2017

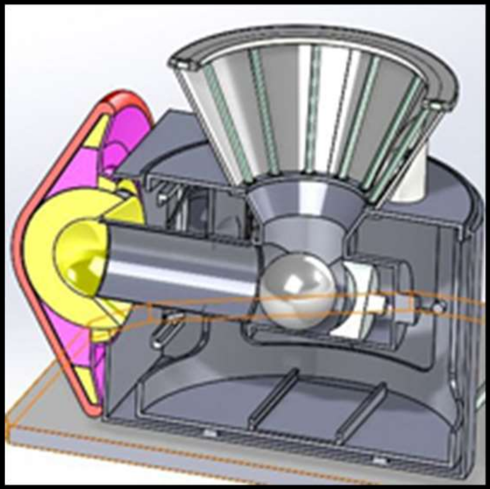
- *Modeling thruster plume induced contamination of the science site on the surface of Europa*



Mars Sample Return (MSR) Concept

Current advanced technology development for a robotic Mars Sample Return (MSR) architecture involve a campaign of three missions:

- MSR-C (fulfilled by Mars 2020) will collect and cache samples with a rover
- MSR-L will retrieve the Cache Canister and launch it into Mars orbit using a lander, rover and a Mars Ascent Vehicle (MAV)
- MSR-O will locate and capture the Orbital Sample (OS) in Mars orbit and return it to Earth



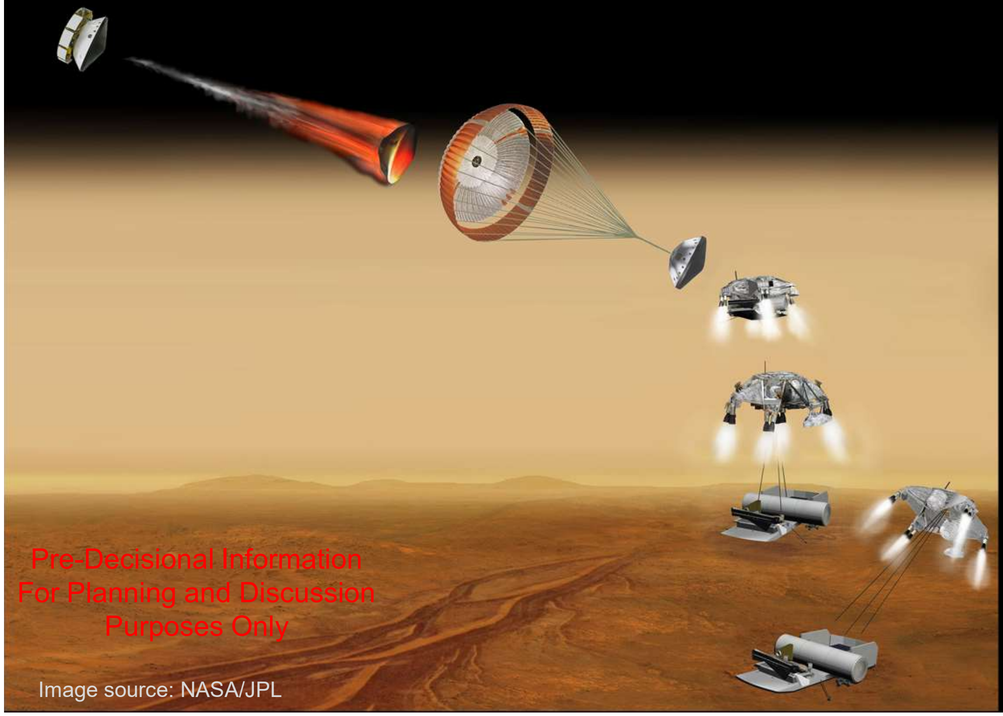
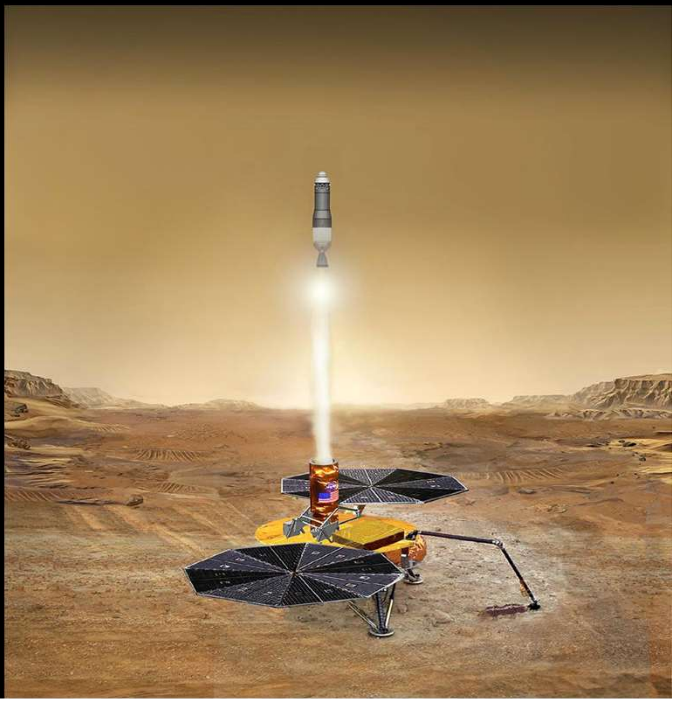
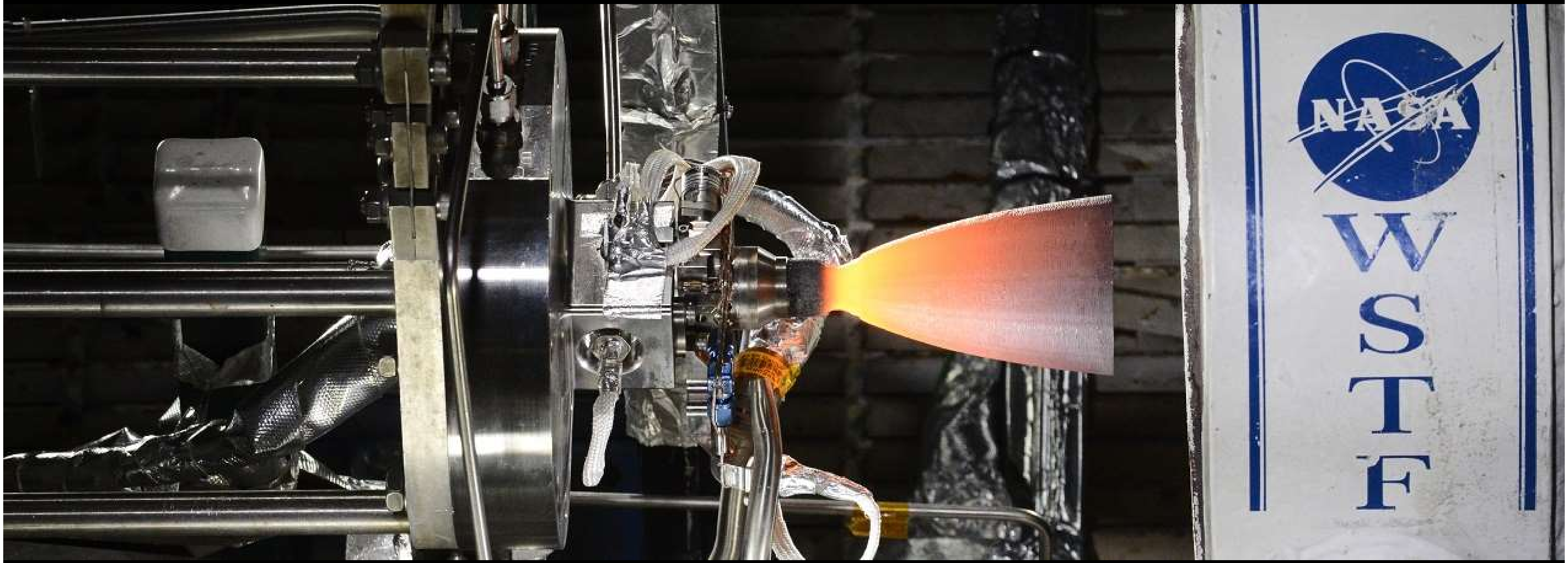


Image source: NASA/JPL



Needed Improvements in the Characterization of Plume Induced Contamination and Erosion



- Knowledge Gaps
- Ground-based chamber testing
- On-orbit flight experiments
- Modeling: time-dependent solutions to transients (start-up/shutdown)

Image source: NASA

Knowledge Gaps

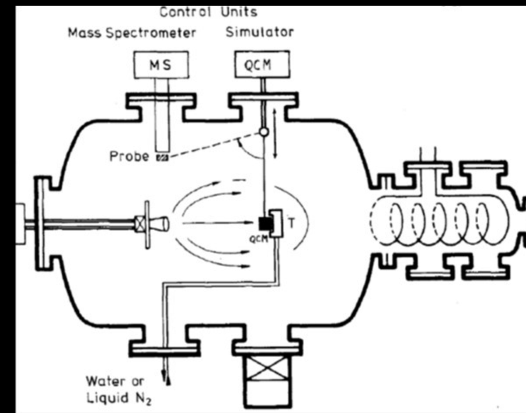
- Modeling and measurements of transient effects (start-up and shutdown) on the production and distribution of droplets and particulates
- Mapping of droplets and particulates in the plume during start-up, steady-state and shutdown phases
    - Production of particulates (iron nitride in bipropellants, catalyst fine ejecta in monopropellants, boron nitride in Hall effect thrusters)
- Distribution (size and number density) of droplets and particulates as a function of angle off plume centerline
- Composition of plume effluents (partial combustion/decomposition reaction products, non-volatile residue)
- Optical properties of plume deposits

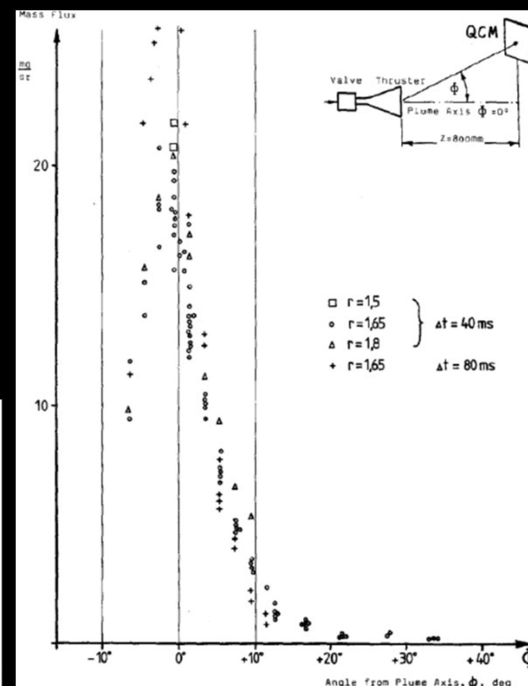
Source: Lumpkin, F.E., Albyn, K.C. and Farrell, T.L., "The Plume Impingement Contamination II Experiment: Motivation, Design and Implementation Plan," AIAA 2001-2815, 35th AIAA Thermophysics Conference, June 2001.

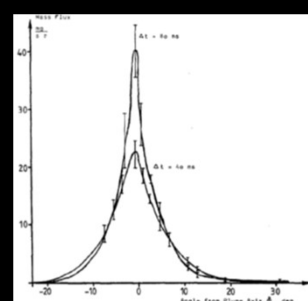
Knowledge Gaps

Chamber-Based Thruster Testing

- Chamber-based measurements of plume induced contamination were primarily made in the 60's, 70's and 80's
  - U.S.: NASA (JPL, GRC, WSTF), U.S. Air Force (AEDC, AFRPL), Lockheed, General Electric
  - Europe: TU Hamburg, MBB/ERNO, ESRO/ESTEC, DLR
  - Russia: Keldysh, RSC-Energia
  - **Limited measurements/data:**
    - **mostly of qualitative nature**
    - **most measurements within 40° centerline**



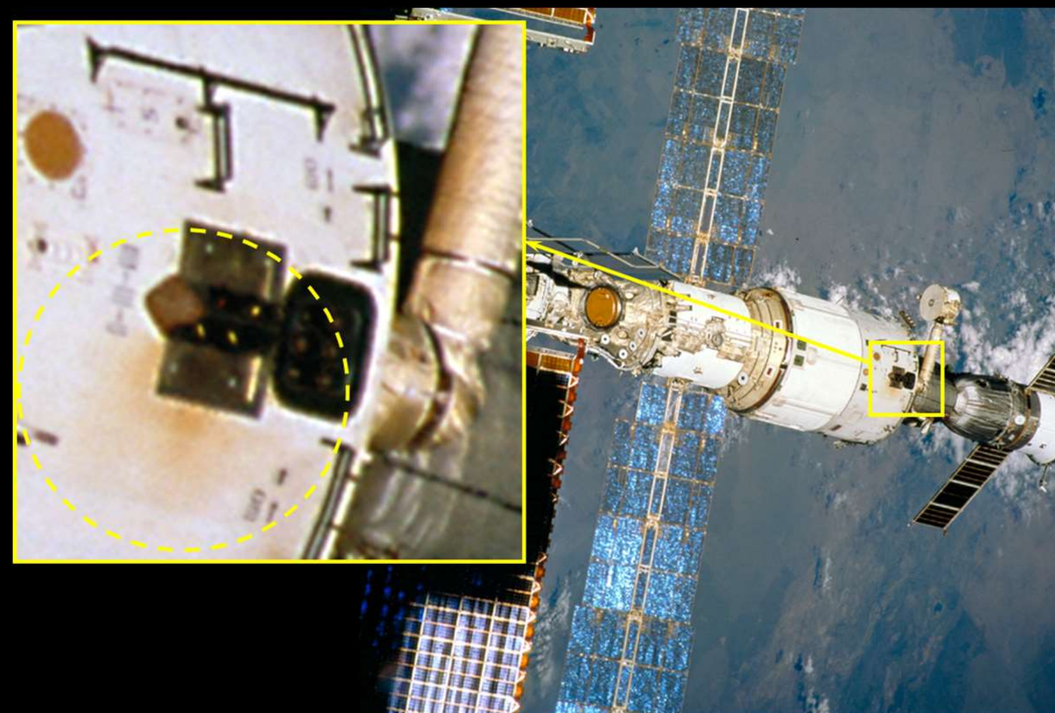


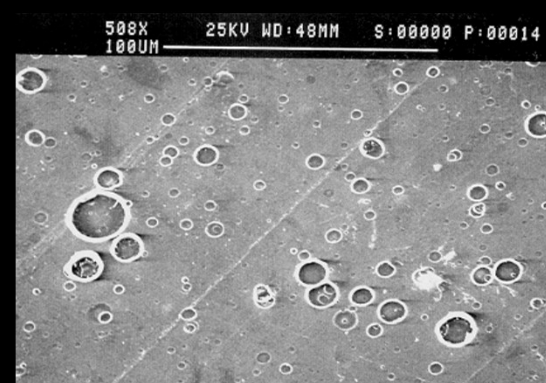


Source: Trinks, H. and Kalsch, I.; "Experimental Exhaust Plume Investigation with MBB 10N Bipropellant Thruster," MBB UR 558-84, ESA/ESTEC Contract 4888/81/NL/AK, December 1983

Knowledge Gaps
On-Orbit Flight Experiments

- On-orbit flight experiments:
  - U.S.: SPIFEX and PIC
  - Russian: Kromka, SKK
  - **Limited flight experiment measurements/data:**
    - **most measurements near plume centerline**





Source: Soares, C. and Mikatarian, R., "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments", SPIE 4774-20 International Symposium on Optical Science and Technology, Seattle, July 2002.

The need for a roadmap for the future

Modeling:

- Transient effects (thruster start-up and shutdown)
    - Time dependent CFD/DSMC solutions with droplet/particle tracing capability
    - Film cooling effects

Chamber-based testing

- Quantitative and systematic measurements
- Gas-phase condensation at low temperatures (outer solar system missions)
- Mapping of liquid and solid-phase from plume centerline through high-angles and backflow
    - Size and velocity distributions
- Transient effects (start-up and shutdown)
- Erosion effects (impacts)
- Composition and toxicity of contaminant deposits (transient and permanent)
- Optical properties of deposits

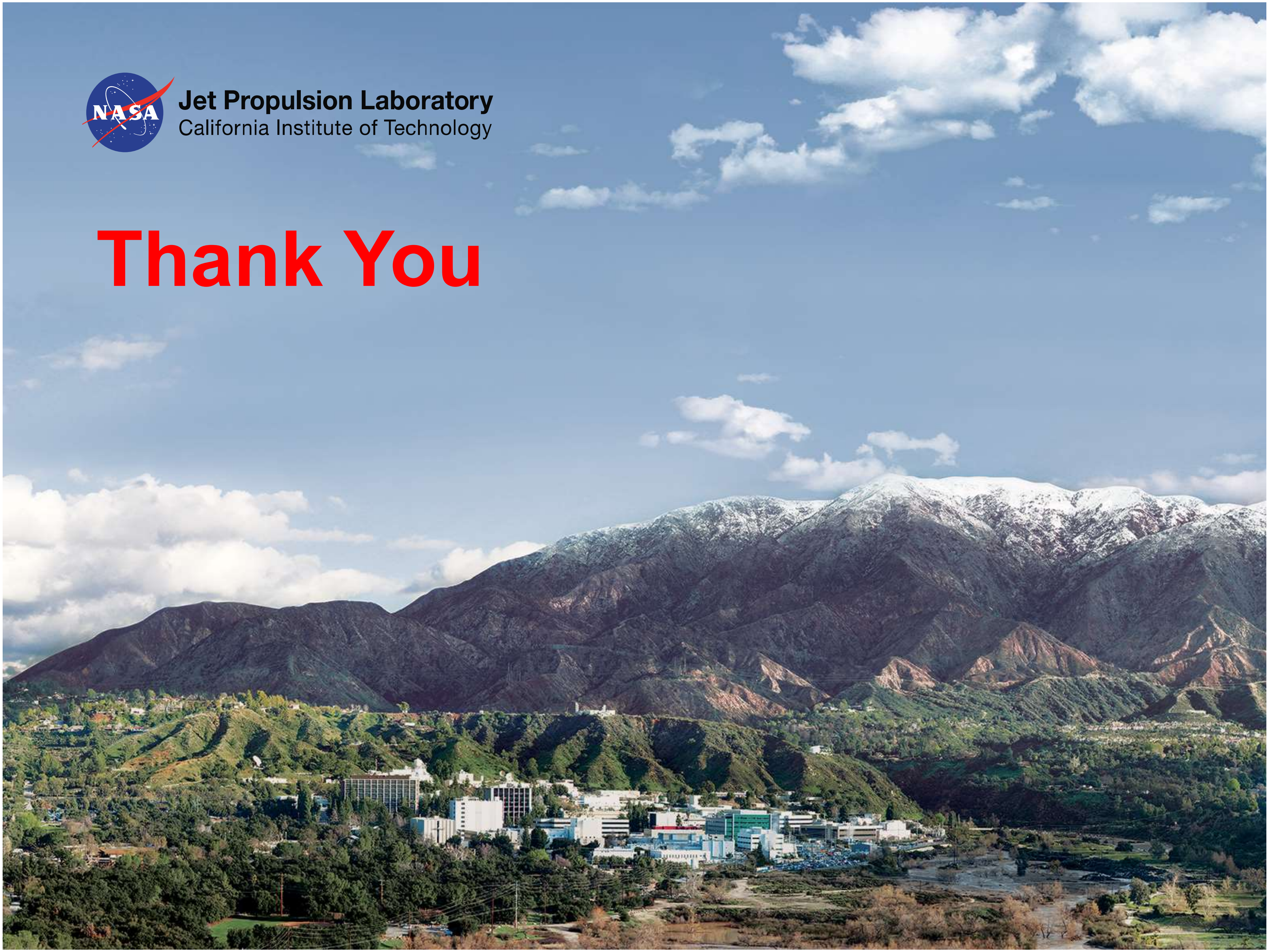
The need for a roadmap for the future (concluded)

On-orbit flight experiments

- Full plume expansion in vacuum
- Combined effects with ultraviolet and high energy radiation, atomic oxygen exposure, combined effects with other contaminant deposits (siloxanes and hydrocarbons from outgassing)
- Liquid-phase characterization (deposits and impacts) from plume centerline through high-angles off centerline and backflow
- Solid-phase characterization (impacts)
- Erosion and mechanical damage characterization
- Deposit composition and toxicity
- Optical properties of contaminant deposits

Conclusions

- Characterization and mitigation of plume induced contamination and erosion effects is critical to space exploration and achievement of mission science objectives
  - Mission science objectives supporting detection of organics and life are extremely challenging
  - Science instrumentation is evolving with increasing sensitivity to spacecraft induced environments
  - Existing measurements/data, both from ground-based chamber tests and on-obit flight experiments, is very limited
  - Engineering plume induced contamination and erosion models exhibit significant levels of uncertainty due to limitations in available measurements/data
- Knowledge gaps are known and can be addressed through ground-based chamber testing and on-orbit flight experiments
- There is a need for the technical community to establish and implement a road map for the future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